Evolving accident scenario modelling in complex processing facilities

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Abstract

Offshore oil and gas production and processing facilities are prone to incidents such as leakage which may escalate thus causing major accidents. These accidents pose a serious threat to personnel and assets. Previously, accident modelling has relied on studying a single event and its impact. It has been witnessed from past events that accidents are caused by combinations of events and therefore, accident modelling must consider multiple sequences of events and interdependent factors.

The Floating Liquefied Natural Gas (FLNG) is a complex processing facility where a leakage of liquified natural gas (LNG) may escalate to a range of events such as fire to vapor cloud explosion. The escalation of events is dependent on the multiple intertwined factors evolving with time and space. This study is focussed on developing novel methodologies and models to study the transitional events and their causation during a major event in complex LNG processing facilities.

This thesis outlined an extensive literature review and analysis of offshore and marine safety from the perspective of fire and/or explosion accidents. It analysed various causes of fire and/or explosion accidents and proposed a series of countermeasures with respect to different causes. The impact of the cryogenic temperature of LNG on steel structure during its accidental leakage has not been extensively studied. This study modelled an LNG pool formation and the impact of cryogenic temperature on a structural material during an accidental release of LNG. The study confirmed that an instantaneous LNG pool formation does cause immediate failure, however, this may significantly minimise design life of the structure and due attention is needed throughout its service life particularly in the spilled area. Literature review showed that minor leaks occur frequently, and they are often overlooked assuming that they are inconsequential. However, in the case of LNG, it can be too simple to ignore small leak due to the potentiality of causing suitable scenario for fire and explosion event upon rapid vaporisation after the leakage. This study proposed a novel technique for modelling fugitive leakage of LNG in a processing facility. The developed methodology is applied considering three different degrees of congestion and revealed that higher congestion levels present higher flammable hazards than the lower levels of congestion within the acceptable congestion level. As fire is the main cause of accident in oil and gas processing facilities, this study proposed a novel methodology for modelling fire impact assessment in a typical FLNG processing facility using Computational Fluid Dynamics (CFD). Three most credible fire accident scenarios were chosen from among various fire scenarios considered in the FLNG facility. It is found that the scenario in the Mixed Refrigerant Module in the liquefaction process presents the highest risk of fire to both on-board personnel and assets. In a complex processing facility, there is a high likelihood of occurrence of transitional scenarios such as hydrocarbon release, fire, explosion and dispersion of combustion products. Finally, this study modelled potential transitional events and their integrated impact during an accidental release of LNG. This study revealed that in a complex processing facility, transition of events is highly possible, and the impact of such events can be more severe than that of the individual event.

This study serves as a comprehensive source of knowledge and technique on which to model various accident scenarios. The study of these scenarios assists in better understanding of accident causation and improves design to prevent causation of such events. The study also provides a practical approach to design safety measure to control and mitigate hazards when prevention is challenging. This thesis will serve as a guiding book to better design of processing facilities and safety measures for a complex processing facility.

Declaration and Statements

Declaration of Originality

I declare that this is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been duly acknowledged in the text and a list of references is given.

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Thesis by Journal Articles

The following journal articles constitute five chapters of this thesis. The third chapter is currently under review in Journal of Loss Prevention in the Process Industries. The fourth chapter is under review in Journal of Loss Prevention in the Process Industries. The sixth chapter is submitted for potential publication in Process Safety and Environmental Protection Journal.

- Chapter 2: Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., Dadashzadeh, M., (2018). Review and analysis of fire and explosion accidents in maritime transportation. *Ocean Engineering* 158, 350-366. doi: 10.1016/j.oceaneng.2018.04.022.

- Chapter 3: Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., (2018). Aging and Failure Analysis of LNG Spill on Steel Structure in Congested Marine Offshore Facility. Submitted to *Journal of Loss Prevention in the Process Industries*.

- Chapter 4: Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., Dadashzadeh, M., (2018). Accidental release of Liquefied Natural Gas in a processing facility: effect of equipment congestion level on dispersion behaviour of the flammable vapour. *Journal of Loss Prevention in the Process Industries*.doi.org/10.1016/j.jlp.2019.07.001.

- Chapter 5: Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., Dadashzadeh, M., (2017). Fire impact assessment in FLNG processing facilities using Computational Fluid Dynamics (CFD). *Fire Safety Journal* 92, 42-52. doi: 10.1016/j.firesaf.2017.05.012.

- Chapter 6: Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., Dadashzadeh, M., (2019). Modelling an integrated impact of fire, explosion and combustion products during transitional events caused by an accidental release of LNG. *Process Safety and Environmental Protection* 128, 259-272. doi: 10.1016/j.psep.2019.06.005.

Published works not included in this thesis, but can be accessed as supplementary materials are given below:

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- Baalisampang, T., Abbassi, R., Khan, F., (2018). Overview of Marine and Offshore Safety, *Methods in Chemical Process Safety*, Vol. 2.

<u>Statement of Co-Authorship Template</u>

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Chapter 1

Introduction

1.1. Background

The global demand for natural gas is rising at a time when the world needs to respond to the threat of climate change. Over the few decades, global consumption of natural gas has been growing at very high rate and it is the fastest growing fuel [1, 2]. It has been predicted that about a quarter of the global natural gas remains in remote and stranded offshore reserves where conventional production techniques may not be economically feasible [3]. It is estimated that over 75% of the world's proven natural gas reserves are inaccessible by pipeline and a majority of those reserves exist in remote location where conventional production techniques cannot be economically feasible [4]. Pressures have been mounted to exploit such gas reserves because of increasing demand for clean fuel. Therefore, oil and gas industries need to find a feasible and viable solution to monetize such gas reserves. This need has led to the development of other technologies such as Compressed Natural Gas (CNG), hydrate transports, Gas to Liquid (GTL) and LNG technologies. It has been proposed that remote and stranded offshore gas reserves could be better exploited by applying GTL or LNG based Floating Production Storage and Offloading (FPSO) [5]. To meet increasing demand for natural gas and to monetize marginal and stranded gas fields, a Floating Liquefied Natural Gas (FLNG) processing facility is foreseen as a promising technology. Using an FLNG processing facility, the natural gas can be economically and commercially produced and exported in the form of LNG from remote and stranded reservoirs located far from shore [6]. The revolutionary concept of FLNG is obtained from a mixture of land-based LNG industry, offshore oil and gas industry and marine transport industry [7]. The FLNG opportunity is growing in all regions because of its flexibility in operations and the added economic and environmental advantages such as reducing the number of elements in the supply chain and decreasing capital expenditures. Additionally, it has a lower environmental footprint and has the capability of relocation once the gas field is depleted [8].

As a result, several FLNG projects are being proposed and developed. On April 2017, PETRONAS' first FLNG facility (PFLNG SATU), became the first FLNG to successfully load cargo [9]. As of 2016, 24 FLNG developments were in progress, 7 under construction and 17 in the planning/pre-engineering stage [10]. The FLNG technology seems to be an effective economic solution for monetization of stranded offshore gas reserves and is increasingly becoming a viable option for the future natural gas market. Despite having promising advantages over traditional techniques, FLNG has some technical and operational challenges such as integration and operation of land-based technology in oceanic environments, operational risks, offloading in hostile conditions and the effects of sloshing in storage tanks. Due to the complex and congested geometries or layouts, motion effects and hazardous operations, these challenges and hazards are higher in an FLNG processing facility in comparison to onshore LNG plants of similar capacity [3]. There are inherent challenges in the development and operation of FLNG because of the large size with complex geometries and hazardous operations, new technology and inadequate experiences or references or lesson learnt. Moreover, it may usually be located far offshore where there is a high likelihood of harsh environmental conditions and standard approaches may not be adequate for the integration of land-based technology in an offshore environment.

In a complex processing facility such as an FLNG facility, process accidents are of major concern. Accidents are often caused by equipment malfunction, process deviation, structural failure and/or human error. Inadequate controls and safety measures can lead to an increase in the severity and frequency of accidents. This has been reflected in several major accidents such as the Piper Alpha disaster [11], the Ocean Ranger accident [12], and BP Deepwater Horizon [13] that have occurred in the past few decades. Accidents in processing facilities are mainly associated with fire, explosion and toxic product releases [14]. Offshore production, storage and transportation of LNG pose more severe hazards in comparison to conventional methods of producing natural gas. An accidental or intentional release of LNG presents several hazards such as frostbite, asphyxiation, metal embrittlement, fire and/or Vapour Cloud Explosion (VCE) [15].

In an FLNG processing facility, accidental release of LNG does not simply lead to one single event with its individual consequence. It often begins with a minor single event which escalates into more damaging events. For instance, accidental leakage of a small quantity of LNG may be a single minor event. However, due to instantaneous vaporisation, it is likely to cause several further events such as pool fire, fireball, flash fire, and VCE if the vapour becomes ignited. When the fire is escalated to a storage facility, it may then cause Boiling Liquid Expanding Vapour Explosion (BLEVE). Many literatures [16-18] have reported the possibility of BLEVE when LNG tank is subjected to an external fire. This has been observed in the past accidents such as the Zarzalico accident on 20th October 2011[19]. The fireball, VCE and BLEVE can cause more damage and become the dominant consequence. In most cases, these types of events result in catastrophic consequences. For instance, the Deepwater Horizon disaster resulted in total loss of the platform after a sequence of accidental releases of hydrocarbons, explosion and fire events which later escalated [13]. Even a small release of LNG in an FLNG processing facility has the potential to present serious risks because of the increase in volume 600 times under ambient conditions. Past studies into LNG hazards and risks have been carried out considering large spill, mostly in simple geometries such as open space, on water surface, trenches and impoundments [20-22]. These studies have revealed some fundamental understandings of LNG hazards or risks. However, due to the complexities involved in the conduction of such tests/or studies in realistic scenarios, accidental release of LNG and its hazards are not modelled and assessed by considering complex layouts such as layout of an FLNG processing facility. Majority of studies [23-25] relating to LNG safety have considered only a single event and phenomenon. During a fire and/or VCE, effect of combustion products plays a significant role in causing fatality or injury [26]. Thus, it is essential to incorporate effects of combustion products with thermal radiation and overpressure in consequence modelling. This can be achieved by considering evolving accident scenarios (release, dispersion, fire and explosion) in consequence modelling because in this modelling complete causes and effects of a series of events can be considered in a single model and an integrated impact can be generated. This merit has provided a motivation to model various potential events likely to be caused by an accidental release of LNG in a complex layout. This study provides an insight into the broader approach to model potential transitional events in any complex processing facility and plays a vital role in risk assessment in a complex processing facility.

1.2. Motivation and research objectives

As the demand for LNG continues to rise, it is important to understand risks associated with its production, handling, storage and transportation. In complex processing facilities, accidental release of LNG has potential to a cause number of events such as fire, explosion, and toxic/combustion product release. Safety of those facilities highly depends on an effective modelling and assessment of those events and appropriate design and implementation of safety strategies. Based on a comprehensive literature review, this study addresses the following research gaps.

1. The marine and offshore operations have been susceptible to several hazards such as collision, capsizing, foundering, grounding, stranding, fire, and explosion [27]. Fire is the most frequent accident in process facilities and in the transportation of hazardous materials [14, 28]. Considering fire and explosion as major accidents, fire accounts for 59.5% of these accidents in process industries [29]. Fire and/or explosion accidents are often caused by more than one contributing factor through complex interaction [30]. Accidental release of fuel or lubricating oil in the engine room or power generation system is one of the most common causes of fire and explosion event due to availability of ignition sources such as sparks and hot surfaces. Identification of root and contributing causes and their interaction are important to understand and prevent such accidents. There is a need for a comprehensive review of causes and preventative measures of fire and explosion accidents in marine operation. Flammability of a fuel is one of the key properties that defines its hazard severity. The flammability of different fuels needs to be compared from safety perspectives. According to a DNV report [31], alternative fuels that are already used or could potentially be used in the future include LNG, Liquefied Petroleum Gas (LPG), biofuels, synthetic fuels (Fisher-Tropsch) [32], methanol and ethanol, Di-Methyl Ether (DME), biogas, hydrogen, biodiesel nuclear fuel and electricity. There is a need for better understanding of the effectiveness of alternative fuels in mitigating fire and/or explosion hazards.

   In the current study, a chapter is dedicated to analysis and review of fire and explosion accidents in marine and offshore facilities. Moreover, effectiveness of alternative fuels in mitigating fire and explosion hazards has been reviewed based on the comparison of their flammability properties.

2. Most studies [24, 33, 34] have paid attention to fire scenario in a module or unit of a facility using scenarios which may not be adequate for fire safety analysis for the whole facility. In complex and large facilities such as FLNG processing facilities, there can be hundreds of probable fire scenarios and randomly selecting a scenario for fire modelling may neither be appropriate nor reasonable. As there are very few experiences of operating FLNG processing facilities, modelling a real scenario may not be feasible. To avoid this limitation, various credible fire scenarios need to be developed and assessed to find the most credible fire accident scenarios. Moreover, there is no study available, particularly for fire risk and consequence assessment of FLNG processing facilities incorporating credible scenarios in all topside modules. There is need for a comprehensive study of different fire scenarios in FLNG facilities because of the inherent challenges posed by the operational complexity in

a congested space, harsh environment and lack of adequate experiences or references [35]. This study proposes a methodology to define the most credible accident scenarios and to simulate impacts of a fire event in an FLNG facility using Computational Fluid Dynamics (CFD) code Fire Dynamics Simulator (FDS).

3. Some large-scale experiments and tests were carried out to gain an understanding of major spill and dispersion characteristics of LNG. These included the Burro series [21], Coyote series [36], Falcon series [20], Maplin Sands tests [37], Esso tests [38], Shell jettison tests [39], Avocet [40], and Brayton Fire Training Field (BFTF) [41]. However, tests or modelling of a minor LNG leakage and dispersion in a complex layout has not received due attention. Minor leakage often represents only a small source of all leaks and seems to be inconsequential. However, if its flammable concentration reaches an ignition source then it may cause various transitional events leading to catastrophic consequence. On the other hand, an accumulation of many minor leakages, from any source or group of sources, becomes a major release into the air equivalent to a large release. According to an HSE report [42], more than 50% of the total hydrocarbons (HCs) release incidents are minor. Given the high frequency of minor leaks and high potential to trigger major accidents, small leaks and their dispersion may be too simplistic to ignore. This confirms the significance of effective modelling of minor leakage and its dispersion to avoid evolving scenario events such as personnel incapacitation, fire and explosions. In comparison to onshore facilities, modelling of gas dispersion in an offshore facility may be generally more complex due to complex geometries and layouts. Moreover, in complex layouts and congested areas, the adequacy and the effectiveness of a detection system may be difficult to determine, and compact layouts and equipment congestion may cause difficulty in the monitoring of small leakages and the pockets of accumulated vapour may remain undetected. Therefore, an FLNG processing facility is expected to have higher risk of vapour cloud dispersion and explosion due to processing, storage and offloading of LNG and other flammable products under harsh environmental conditions. Because of this, modelling the leak and dispersion characteristics of LNG vapour is an important aspect of FLNG processing facility risk assessment and management. Therefore, in this study, a minor leakage is investigated in a typical processing facility and then dispersion characteristic of LNG vapour is modelled considering FLACS codes.

4. A controlled venting of cryogenic vapours (LNG) from storage is usually not hazardous. However, accidental release of LNG from a system under pressure, or a large quantity spill, can give rise to serious hazards [43]. LNG is a cryogenic liquid having temperature about –160 °C to –162 °C [15]. According to Bilstein [44] most researchers consider a gas to be cryogenic if it can be liquefied at or below 240 °F (-150 °C). The typical temperature of LNG is much lower than the ductile to brittle transition temperature of common structural materials [15]. Accidental spill of LNG on structural material can reduce its temperature significantly and the material can undergo thermal contraction [45]. Currently, failure of an LNG storage tank subject to contact with cryogenic temperatures has been extensively studied [46, 47]. In order to predict how a structural section of an LNG vessel would respond when it comes in contact with cryogenic LNG, Petti and Kalan [48] conducted a series of large scale LNG spill and fracture tests on ABS Grades A and EH steels. These tests were conducted exposing test material (steel plate) for a prolonged period and focussed on immediate crack growth. However, impact assessment of an instantaneous small quantity spill of LNG has not received much attention including its long-term impact. This study proposes a novel methodology for assessing the impact (both immediate and long-term) of minor leakage of LNG on structural steel considering LNG spill and pool formation modelling, and static structural analysis.

5. In most risk assessments and investigations of fire and explosion events, it has been found that a single phenomenon is usually considered for consequence analysis [23, 25, 49, 50]. Dadashzadeh *et al.* [50] modelled dispersion of flammable gas integrating with explosion consequences of the BP Deepwater Horizon explosion using FLACS. Smoke and heat radiation released from the fire also affect human health and offshore structures, however, these impacts were not considered for consequence analysis in this study. Dadashzadeh *et al.* [23] proposed a methodology for toxic risk assessment during LNG fire using FLACS. However, the direct consequence of fire was not considered. Baalisampang et al. [51] modelled impact of fire in a typical FLNG processing facility, but other potential events and consequences were not incorporated in the study. In most cases though, fire, VCE and combustion product release occur one after another or simultaneously resulting in an integrated consequence. Past accidents and models demonstrate that the need to evaluate the entire accident sequences [52]. In fire and explosion accidents, the damage potential (radius) due to fire and explosion is less than that of inclusion of combustion/toxic product releases [23]. Safety measure design and emergency preparedness is not very effective if an

integrated impact is not considered due to inclusion of incomplete effects. By acknowledging the significance of this, some key studies were carried out including that by Khan and Amyotte [53] who proposed a methodology that incorporates fire, explosion and toxic release damage indices to evaluate the inherent safety of a facility based on inherent safety guidewords. Dadashzadeh et al. [54] proposed a methodology for modelling an integrated consequence of both fire and explosion but the impact of combustion product was not included in the risk analysis. Therefore, in this study an integrated impact of fire, VCE and toxic/combustion product release during an accidental release of LNG in a typical FLNG processing facility is studied considering different evolving accident scenarios.

The main research theme of this study is to explore the potential solution to model transition or integration of accident events in a typical complex processing facility. Considering this, the research study includes five different objectives as follow:

1. To review root and contributing causes of fire and explosion accident in marine vessels, and analyse effectiveness and prospect of currently proposed alternative fuels in mitigating fire and explosion accident.

2. To model LNG pool formation, and model the impact of cryogenic temperature on steel structure.

3. To investigate credible fire accident scenarios and to model the impacts of fire event in an FLNG processing facility.

4. To model the dispersion of LNG vapour after minor leakage considering different congestion levels in a typical complex layout.

5. To model transitional events and their integrated impacts in a complex processing facility.

1.3. Novelties and contributions

The novelties and contributions that this thesis made to the accident modelling and consequence analysis are discussed below. These novelties are related to fire impact assessment, dispersion of minor LNG release, impact of cryogenic temperature on steel structure and integrated impact of fire, VCE and combustion product release. This study provides the following novelties:

1. A novel methodology for modelling minor release of LNG and its dispersion in a complex layout.

2. Development of a novel methodology for fire impact assessment in a typical FLNG processing facility.

3. Development of a novel methodology for modelling LNG pool formation and impact assessment of cryogenic temperature on structural steel.

4. Development of a novel methodology for integrating the impacts of fire, explosion and combustion product in a complex processing facility with consideration of evolving scenarios.

1.4. Organisation of the thesis

The thesis is written in manuscript format (paper based) and contains seven chapters (including this chapter). Chapter 2 provides analysis and review of fire and/or explosion accidents in maritime vessels. Various causes of fire and/or explosion accidents are explored, and preventative measures proposed. This chapter is published in the **Ocean Engineering Journal 2018. 158: p. 350-366**. According to this analysis, LNG has been identified as one of the most attractive alternative fuels and its production has been blooming. This stresses the need for comprehensive study of its hazards during an accidental release. Thus, in Chapter 3, a pool formation and the impact of cryogenic temperature on structural material during an accidental release of LNG are modelled using FLACS and ANSYS Workbench 18.1. The developed methodology is applied to a typical layout as a case study. The results showed that an instantaneous LNG pool formation does cause immediate failure, however, this may significantly minimise design life of the structure and due attention needs to be given to the spilled area throughout its service life. This chapter has been submitted to **Journal of Loss Prevention in the Process Industries** for publication.

Another eminent event during accidental release of LNG is dispersion of LNG. Due to cryogenic temperature, LNG vigorously vaporises under ambient conditions and presents several hazards such as fire, explosion and frostbite or asphyxiation. Hazard identification and its management play a pivotal role in safety analysis. Chapter 4 outlines a novel technique for modelling minor LNG leaks and dispersion of vaporised LNG in a complex processing facility.

The developed methodology is applied considering three different degrees of congestion and revealed that the higher congestion level poses higher flammable hazards than the low level of congestion within the acceptable congestion level. This chapter is published in **Journal of Loss Prevention in the Process Industries 2019. 61: p. 237-248**. In complex processing facilities such as an FLNG, fire risk is considered as the most critical risk among all other types of risks during an accidental release of LNG. Chapter 5 presents a novel methodology for modelling fire impact assessment in a typical FLNG facility using CFD. Significance of the methodology is demonstrated with a case study considering different credible scenarios. This chapter is published in **Fire Safety Journal 2017. 92: p. 42-52**. In a congested and complex layout, there is high likelihood of the occurrence of multiple events one after another or simultaneously and this underlines the need of modelling of entire events for appropriate risk assessment and safety measure designs. Chapter 6 presents transitional modelling of different potential events during an accidental release of LNG and an integrated impact is assessed. This study revealed that the impact of transitional events can be more severe than that of an individual event and emphasizes the need for such modelling in any processing facility. The main contribution of this work is the modelling of interactions of potential events in an evolving accident scenario. This chapter is published in **Process Safety and Environmental Protection Journal 2019. 128: p. 259-272**. The final Chapter (Chapter 7) provides detailed conclusions and recommendations of the thesis. It is anticipated that the outcomes of the developed methodologies will provide a great insight into transition or integration of accident events and their consequences in any complex processing facilities. An overview of the thesis structure is illustrated in Figure 1-1.

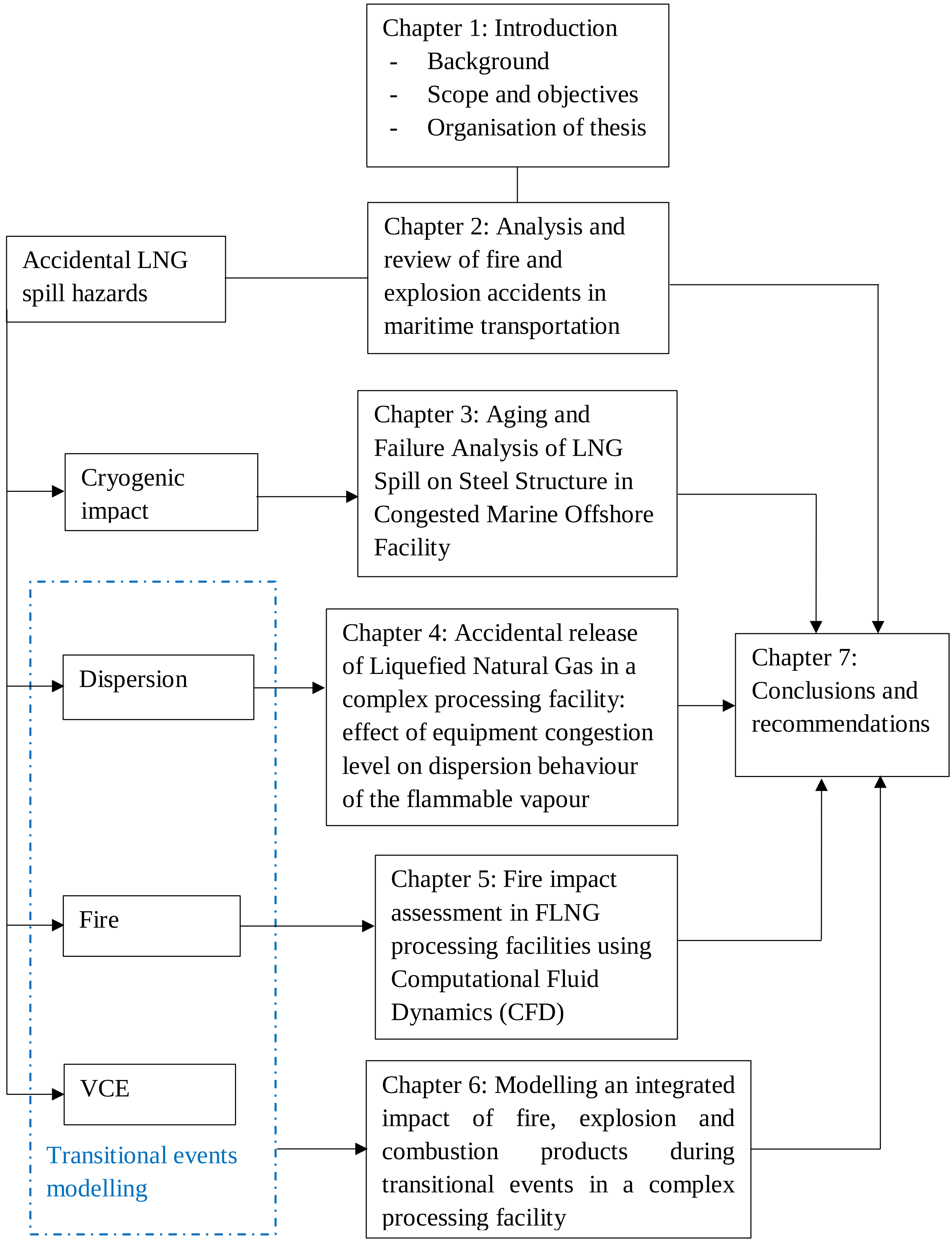

Figure 1-1. Flowchart illustrating dissertation outline and methodology development for evolving accident scenarios modelling.

Chapter 2

Review and Analysis of Fire and Explosion Accidents in Maritime Transportation

Abstract

The globally expanding shipping industry has several hazards such as collision, capsizing, foundering, grounding, stranding, fire, and explosion. Accidents are often caused by more than one contributing factor through complex interaction. It is crucial to identify root causes and their interactions to prevent and understand such accidents. This study presents a detailed review and analysis of fire and explosion accidents that occurred in the maritime transportation industry during from 1990 to 2015. The underlying causes of fire and explosion accidents are identified and analysed. This study also reviewed potential preventative measures to prevent such accidents. Additionally, this study compares properties of alternative fuels and analyses their effectiveness in mitigating fire and explosion hazards. It is observed that Cryogenic Natural Gas (CrNG), Liquefied Natural Gas (LNG) and methanol have properties more suitable than traditional fuels in mitigating fire risk and appropriate management of their hazards could make them a safer option to traditional fuels. However, for commercial use at this stage, there exist several uncertainties due to inadequate studies, and technological immaturity. This study provides an insight into fire and explosion accident causation and prevention, including the prospect of using alternative fuels for mitigating fire and explosion risks in maritime transportation.

Keywords: Maritime accidents, fire and explosion, preventive measures, alternative fuels

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2.1. Introduction

The shipping industry is expanding globally, leading to an increase in worldwide shipping traffic [55-57]. The growing number of marine vessels may lead to a rise in maritime hazards and accidents. Akten [27] stated that shipping is, and always will be, full of risks despite increasing safety standards and improved technology. Celik et al. [58] stated that the system complexity and automation, human error, human-centred system design, and potential design-based failures are different perspectives for ongoing shipping accidents. Due to this, international maritime authorities have made significant efforts to promote safety in the shipping industry [55, 59] but despite this, there are still a high number of shipping accidents reported in recently published statistical reports [60-63]. Shipping accidents by type are numerous, but common examples are collision or contact, capsize, foundering, breaking up, grounding, stranding, and fire or explosion [27]. Broadly, human error, technical and mechanical failure, and environmental factors are common causes leading to shipping accidents but with different percentages [64, 65]. The Major Hazard Incident Data Service (MHIDAS) [66] database, considered eight types of possible causes of general accident, namely mechanical failure, impact failure, human error, instrumental failure, services failure, violent reaction, external events and upset process conditions. According to Allianz Global Corporate and Specialty [67] foundering (sunk, submerged) wrecked/stranded (grounded), fire/explosion, collision (involving vessels), machinery damage/failure and hull damage have been the most frequent causes of losses at sea over the past decade (2007-2016).

Accidents are often assigned to a single category such as grounding, fire or explosion, human error, collision and foundering. This type of categorization ignores the fact that often accidents are caused by more than one contributing factor or sequence of undesirable events [68, 69]. Most literatures relating to shipping accidents [70-72] have highlighted the causal factors for general shipping accidents but root causes of a particular event are often ignored. For instance, human error can lead to collision which in turn may cause fire and explosion. In this case, if there are no causal factors for human error as the root cause, then human error, collision and its subsequent events would not have occurred. In order to prevent the consequences of all these events, causal factors for human error are required to be addressed. This indicates that the determination of root cause and potential safety barriers of any accident type are vital in order to prevent accidents.

In the past, a significant number of shipping accidents involved fire and explosions [61, 73, 74]. For instance, Darbra and Casal [60] found that 29% and 17% of accidents in seaports are caused by fires and explosions respectively. Bulk carrier casualties world-wide, taken from Lloyd’s records between 1980 and 2010, confirm that fires and explosions caused 19% of accidents [70]. Weng and Yang [75] found that the contributing factors in shipping accident mortalities resulting from fire/explosion accidents are, on average, 132% higher than from accidents where no fire/explosions were involved. According to the report presented by Allianz Global Corporate and Specialty [76], about 10% of total losses, between 2006 and 2015, were caused by fire and explosion. From 2007 to 2016, foundering accounts for the highest percentage of losses (50.42%), followed by wrecked/stranded with 20.57% with the third highest contributor fire/explosion (9.95%) [67]. The MIRG project (2017) stated that from 2000 to 2015, among different types of marine vessels in European waters, the largest percentage of ship fires and explosions occurred on cargo ships.

The actual number of fire and explosion accidents could be much higher than the published statistics because of underreporting issues of maritime accidents [77, 78]. It is often found that the number of fatalities from fire and explosion accidents in shipping is comparatively higher than that of other types of accidents. Fire and explosion usually occur unexpectedly which provides little evacuation time for passengers or crew members [79].

This shows that the risk of fire and explosion in shipping vessels is high. The consequence of ship fire and explosion depends on the presence and amount of hazardous materials and the employed preventive and control mechanisms. In the absence of appropriate protection and response, even a small error that leads to a fire and explosion event has potential to cause loss of vessels, environmental pollution, injuries, and deaths due to the instantaneous nature of ship fires [80].

Uğurlu [81] investigated fire and explosion events that occurred between 1999 and 2013 in tankers transporting hazardous liquid cargoes and identified 13 root causes and five causal factors being violation of entry permit (VEP), violation of work permit (VWP), lack of risk analysis (LRA), deficiency in safety management system (DSMS), and deficiency in planned maintenance system (DPMS). This study was conducted in three stages. In the first stage, significance level of the root causes was determined using Fault Tree Analysis (FTA), in the second stage, the causative factors underlying the root causes were determined and in the final stage, the relationship between the causative factors and root causes was determined. The author argued that hot work, electric arcs, static electricity, and combustible gas accumulation are the most significant root causes of fire and explosion accidents in tankers transporting hazardous liquid cargoes and VWP and LRA are the main causative factors of fire and explosion accidents.

In this chapter, the contributing factors for fire and explosion accidents in maritime transportation are reviewed based on published full investigation reports and literatures. Accident investigation reports prepared by different agencies such as National Transport Safety Board (NTSB), Danish Maritime Accident Investigation Board (DMAIB), Australian Transport Safety Board (ATSB), Federal Bureau of Maritime Casualty Investigation (BSU), Transportation Safety Board of Canada (TSB), European Maritime Safety Agency (EMSA) and Marine Accident Investigation Branch (MAIB) are considered. Publicly available fire and explosion related accidents in maritime transportation between 1990 and 2015 are grouped into five categories according to their main causes, namely human error, mechanical failure, reaction, electrical fault and unknown. The percentage of fire and explosion accidents caused by each causal factor is given in Figure 2-1.

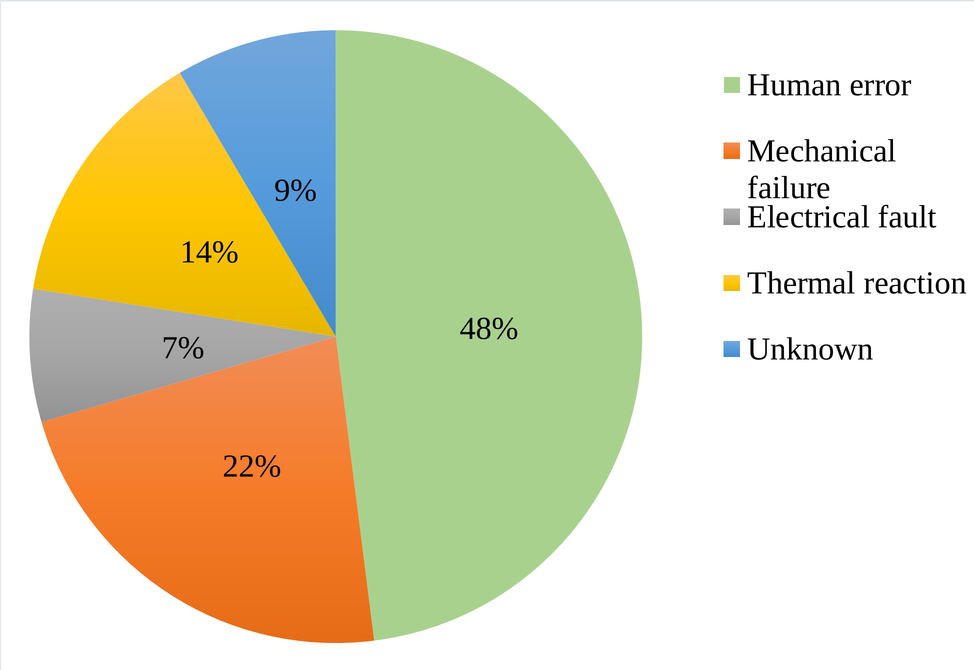

Figure 2-1. Percentages of fire and explosion accidents

These accidents are further divided into different categories in order to compare the number of fatalities and number of accidents in maritime transportation as shown in Figure 2-2. This indicates that fire and explosion still pose a risk to maritime transportation despite technological progress. In order to avoid fire and explosion accidents, a comprehensive review of all contributing factors is essential.

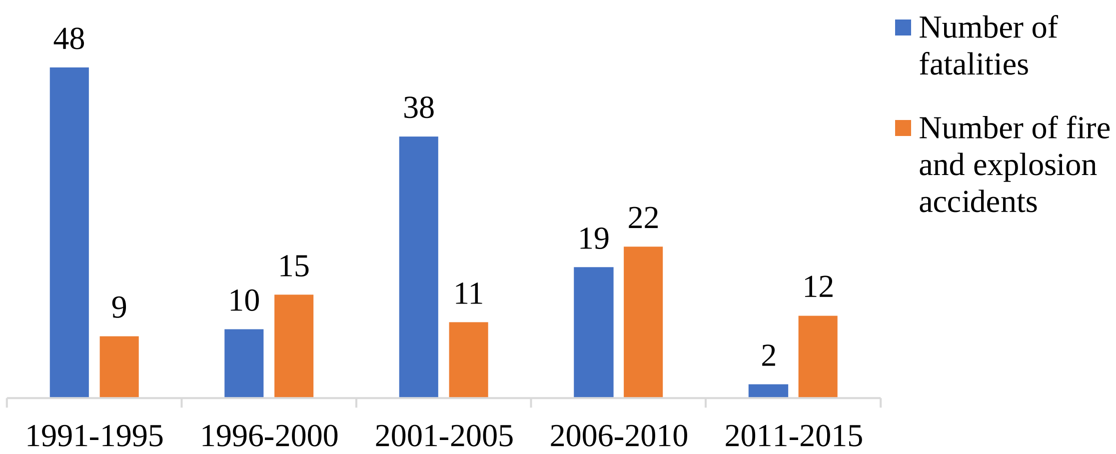

Figure 2-2. Number of fatalities, and number of fire and explosion accidents during 1991-2015

Additionally, in this study, potential preventative or mitigation measures are discussed for each type of contributing factor. Identifying sources of flammable materials and replacing them with less hazardous materials may play a positive role in mitigating fire and explosion risks in ship. Marine fuels are highly flammable. In this study, it is found that 31% fire and explosion events are caused by accidental releases of fuel or lubricating oil in the engine room. Due to this, it is worthwhile to review from a safety perspective flammability property of alternative fuels. The effectiveness of alternative fuels in mitigating fire and explosion hazards is reviewed based on the comparison of their flammability properties. Therefore, this study would help identify contributing factors for fire and explosion events in maritime transportation and would seek to highlight potential preventive measures.

2.2. Fire and explosion accidents causations

The causes of fire and explosion in marine operations identified by Kwiecińska [30], provided characteristics of basic fire causes and the influencing factors in ships. These are namely damage to electrical equipment and cables, damage to mechanical equipment, damage to ship's hull or its equipment, damage caused by external factors, damage occurring during maintenance work/repairs, and spontaneous ignition of cargo. The author has shown the interrelationship of cause-and-effect links leading to fires on ships and argued that spontaneous ignition of cargo is the strongest interaction with other factors. This shows that identifying interrelationships among various causal factors of a broad accident category helps to explore the underlying causes. Thus, in order to identify causal and root causes, contributing factors that were responsible for past fire and explosion accidents in shipping are considered. This can provide different real scenarios of fire and explosion events and help identify real causes and their potential mitigation approaches. An overview of steps undertaken in this study is given in Figure 2-3. This shows that the four causal factors and several underlying causes of fire and explosion accidents are identified using past accidents information and that general preventative measures are proposed qualitatively.

2.2.1. Human error as a cause of fire and explosion accidents

The American Bureau of Shipping (ABS) [82] report stated that marine accidents directly associated with human errors in the MAIB, the ATSB, and the TSB reports total 82%, 85%, and 84%, respectively. This confirms that there is a consistency of causal factor findings among the data and reports in Australian, Canadian, and UK transport accident investigation authorities. This outcome has been supported by other studies [69, 83, 84]. For instance, human error is involved in 75-96% of marine causalities [84]. A study by Wagenaar and Groeneweg [69] showed human error contributed to a total of 96 out of 100 marine accidents. Similar results were reported in Baker and McCafferty [83] where within the period 1991-2001, 80-85% of the maritime accidents were due to human error, 50% were initiated by human error and 30% associated with human error.

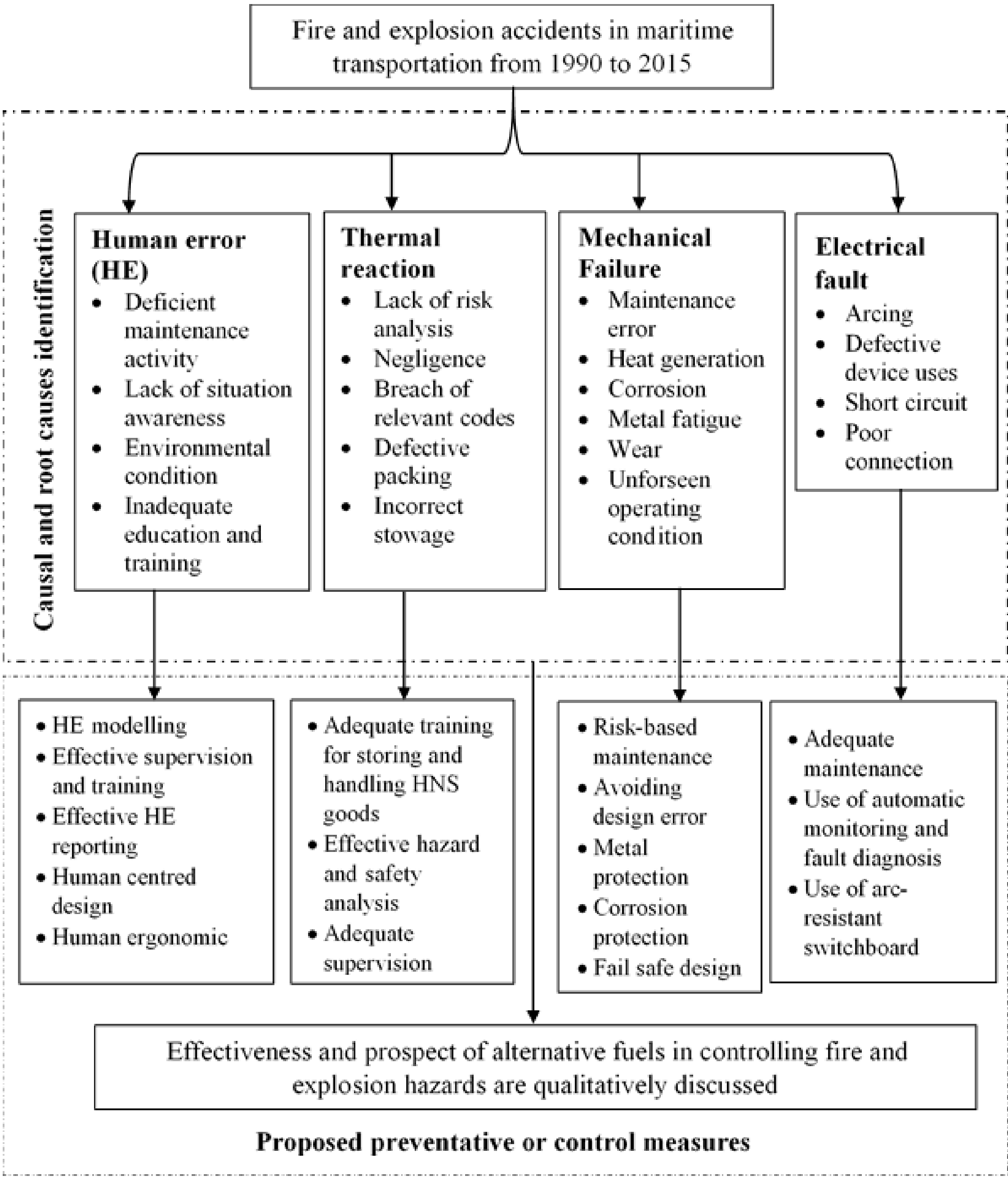

Figure 2-3. Steps undertaken in this study

Apostol-Mates and Barbu [85], stated that human error is related to technology, environment, organisation, work practice and group. The Nippon Kaiji Kyokai - a classification society, [86] broadly divided the factors related to the occurrence of human error into human element, hardware factors, and organisation and management factors. Baker and McCafferty [83] categorised them into five broad groups including situation awareness group, management group, risk group, maintenance human errors and non-human error group and argued that failure of situation awareness and assessment, resulting from human fatigue and task omission, is predominant. Whittingham [87] postulated two types of human error causation namely internal causes leading to endogenous error and external causes leading to exogenous error. An endogenous error relates to an internal cause arising from an individual such as a failure within the cognitive processes. An exogenous error has an external cause such as an unsuitable working environment. Reason [88] discussed human fallibility using two approaches: the person and the system approaches. The person approach is related to errors of individuals, blaming workers for unsafe acts such negligence, forgetfulness, inattention, or moral weakness. The system approach focuses on the existing errors in the workplace and the organisational processes. Based on this concept, human failure is grouped into two categories namely active failures and latent failures. The active failures are the unsafe acts committed by frontline people such as drivers, control room staff or machine operators. The unsafe acts include a variety of practices such as slip ups, lapses, fumbles, mistakes, and procedural violations. The latent failures arise from decisions made by designers, builders, procedure writers, and top level management. Examples of latent failures are poor design of plant and equipment, ineffective training, inadequate supervision, ineffective communications, and uncertainties in roles and responsibilities. Latent failures often remain dormant within the system before they combine with active failures and local triggers to create an accident scenario. These failures can be identified and remedied before an adverse event occurs using proactive risk management strategy [88].

Rothblum [84] stated that the maritime system is a people system where people interact with technology, environment, and organizational factors. Humans may not be the sole cause of an accident and in most accidents are involved in a complex interaction of several factors such as software, hardware, environmental conditions and other humans [89]. Human interaction with other key factors is shown in Figure 2-4. This shows that human factor depends on individual factors such as competency, health, stress and strength, workplace environment (such as site design, ease of use and working condition) and management (procedures, supervision and communications) under which he or she works.

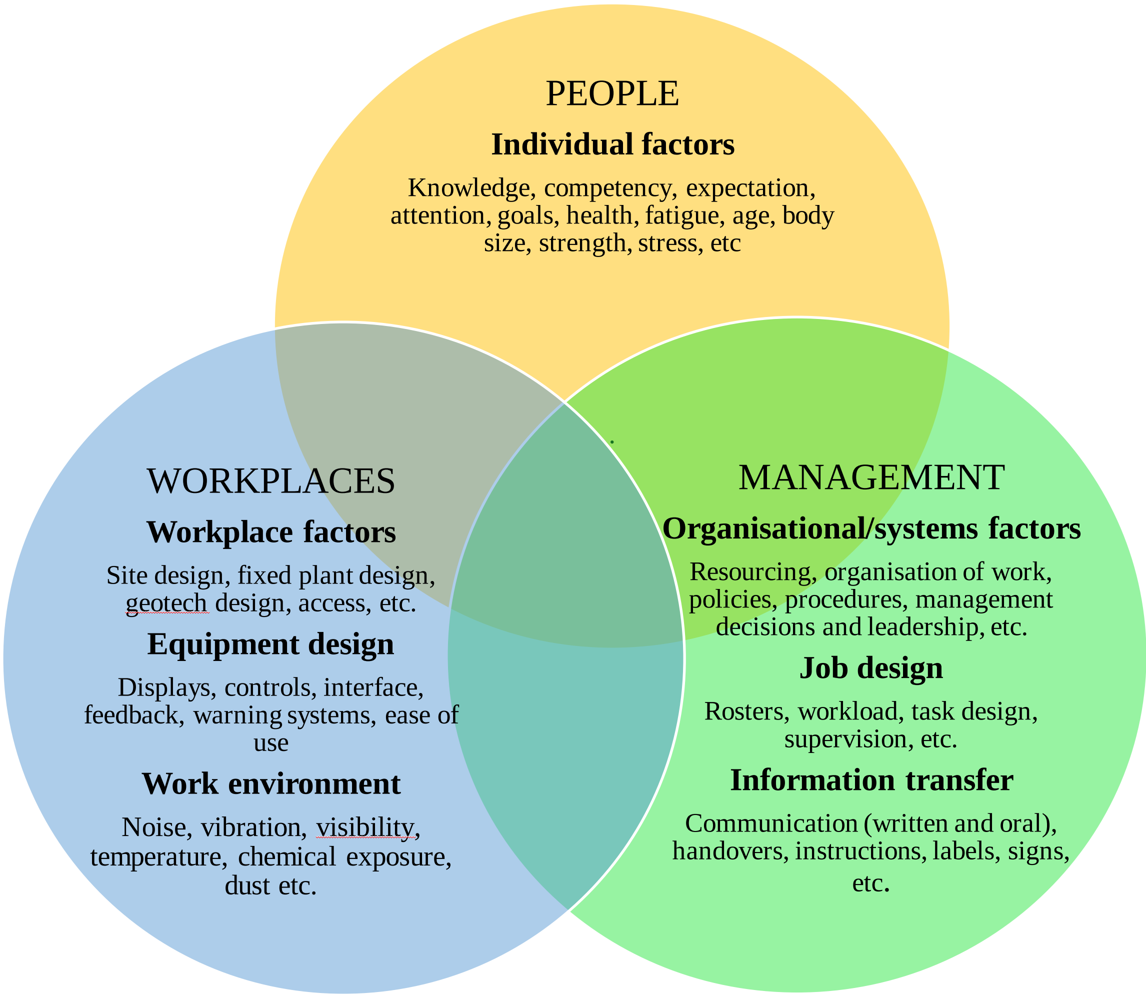

Figure 2-4. Human interaction with other factors [90]

In order to identify underlying causes of human failures, generic human error was functionally deconstructed into logical, mutually exclusive categories into skill based, rule based, and knowledge-based errors, routine violations and singular violation as shown in Figure 2-5.

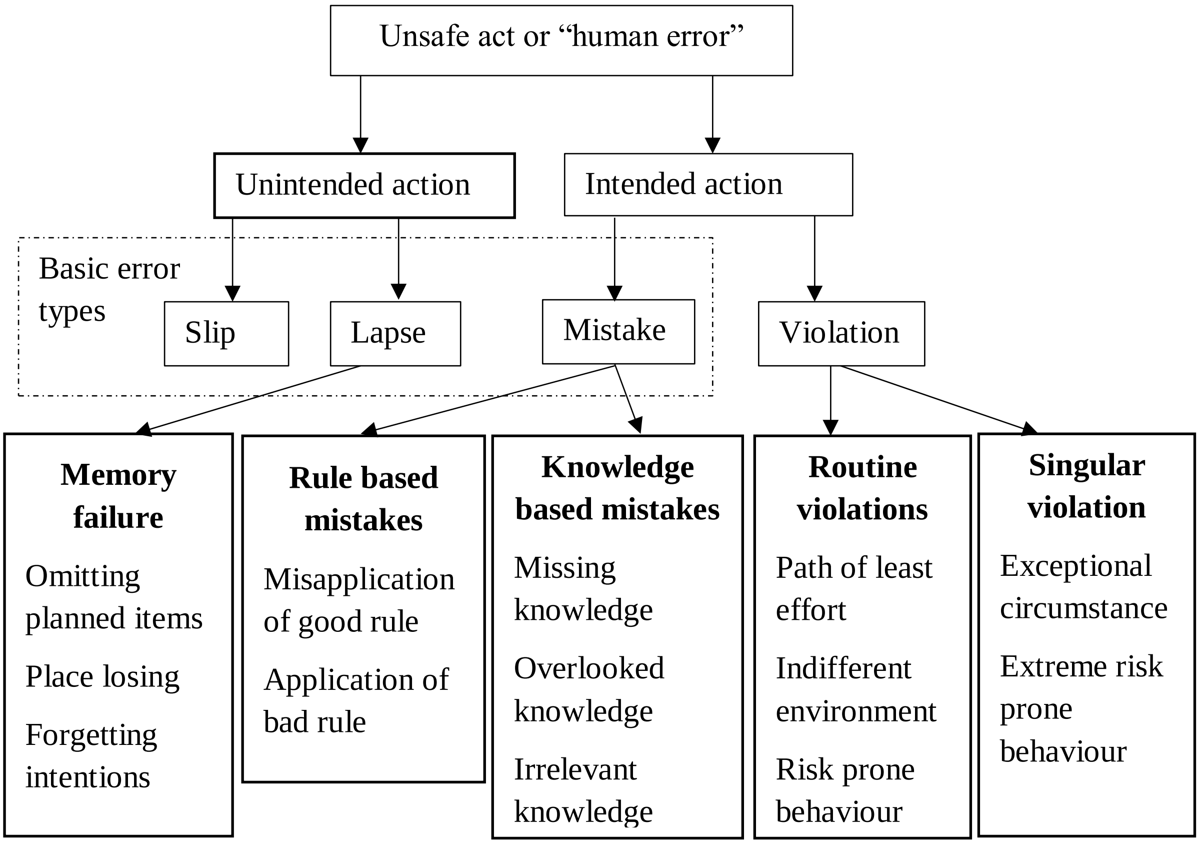

Figure 2-5. Behavioural deconstruction of human error [91].

Celik and Cebi [92] identified various contributing factors of human errors in shipping accidents as given in Table 2-1 and priority weights were generated considering 4 levels of an analytical Human Factor Analysis and Classification System (HFACS). The study argued that skill-based errors, and personnel related factors such as coordination, communication, and planning are the primary causes of shipping accidents in first and second levels respectively. Moreover, inadequate supervision and failure to correct problems, and inadequate organizational processes are the root causes of shipping accidents in third and fourth levels of HFACS.

Table 2-1. Contributing factors of human error on shipping accident

Acts (level 1)	**Preconditions (level 2)**	**Supervision (level 3)**	**Organisational influences (level 4)**
1. Errors a. Skill-based errors b. Judgment and decision making errors c. Misperception errors	1. Environmental a. Physical environmental b. Technological environmental c. Cognitive factors d. Psycho behavioural factors	1. Inadequate supervision 2. Inappropriate operation 3. Failed to correct problem	1. Resource management 2. Organisational climate 3. Organisation process
2. Violations	2. Individuals condition a. Adverse physiological states b. Physical mental limitations c. Perceptual factors 3. Personnel factors a. Coordination/ communication/ planning factors b. Self-imposed stress	4. Supervisory violations	

Among several causes of human error, deficient maintenance is one of the major causes of fire and explosion [93]. This includes inadequate hazard analysis, violation of hot work and confined space entry permit guidelines. Some major accidents include an explosion and fire on the tanker Petrolab [94], boiler explosions on the bulk carrier Shirane [95] and cargo hold fire on BBC Baltic [96]. Dhillon and Liu [97] reviewed human error in maintenance and concluded that human error in maintenance was a pressing problem. Chang and Lin [98] reviewed 242 accidents that occurred between 1960-2003 in storage tanks and revealed that fire and explosion accounted for 85% of these accidents and 30% of accidents were caused by human errors including poor operation and maintenance. Okoh and Haugen [99] stated that about 30–40% of all accidents and precursor events in the chemical processing industry are due to maintenance-related factors. In another study conducted by Okoh and Haugen [93] revealed that among 80 maintenance related major accidents, explosion was involved in 44% of these accidents followed by fire (34%). Hemmatian et al. [100] also revealed that human error occurred mostly in general maintenance activities. In the current study, maintenance related errors were observed in 43% of human error accidents. The fire and explosion on the chemical tanker Bow Mariner in the Atlantic Ocean can be considered as an example of a major accident due to human error in a maintenance related activity. The accident occurred during the cleaning of residual Methyl Tert Butyl Ether (MTBE) by the crew. The accident caused 21 losses of life and the release of a large amount of MTBE, Ethyl Alcohol, heavy fuel oil and diesel into the environment [101]. Use of unskilled crew and lack of situation awareness was reported to be the cause of the accident [102]. Another accident was the explosion of the Tanker Qian Chi in 2011 that led to the serious injury of three crew and caused severe damage to equipment [103]. The improper installation of the thermal oil heater burner nozzle was reported to be the cause of this accident. Consequently, the fuel found its way to the burner and accumulated before the start of ignition. The furnace exploded when the igniter started. The IIWG report [104] stated that the majority of incidents involved MARPOL Annex II substances (rather than oil) and were caused by tank cleaning, venting or gas freeing. Celik and Cebi [92] HFACS investigated human errors in shipping accidents and argued that disorganisation in maintenance planning and management processes are significant factors in contributing to human error. Okoh and Haugen [93] discussed failure scenarios associated with maintenance activities and argued that lack of barrier maintenance, deficient design, organization and resource management and deficient planning/scheduling/fault diagnosis are the most frequent causes in terms of the active accident process, the latent accident process and the work process respectively. Deficient maintenance work also introduces new hazards particularly in safety-critical maintenance works and these are generated by application of new, invalidated procedures, processes, conditions and equipment or existing under validated ones. For example, an explosion and fire occurred in the Partridge-Raleigh oilfield in 2006 during welding of an open-ended piping left unisolated after a previous maintenance session [105].

Another factor responsible for human error is environmental conditions. Substandard physical working conditions may deter the effective performance of duties, causing stress and fatigue. One example of poor working conditions includes physical exhaustion due to high temperatures. High sea states, vibration, noises, and unsuitable temperature can also affect one’s ability to work and can cause stress and fatigue. The environment refers not only to weather and other aspects of the physical work environment, but also the regulatory and economic climates [84]. Moreover, tight economic conditions may increase the probability of risk-taking and may put enormous pressure on one's working conditions. Ambient environmental considerations also include appropriate design of living spaces that assist in recovery from fatigue.

Every human error may lead to a condition necessary for an accident to occur which means that if there is no human error, a chain of events may break, and the accident may not transpire. Hence, by employing appropriate means of preventing some human errors or increasing their detection probability in marine applications, one may provide a higher level of marine safety with fewer number of casualties [84].

2.2.2. Mechanical failure as a cause of fire and explosion accidents

Fire and explosion accidents initiated by mechanical failures have resulted in catastrophic consequences in the past. According to the Allianz Global Corporate and Specialty [67] report, mechanical failure was the fifth highest reason for ship losses from 2007 to 2016. Darbra and Casal [60] revealed that mechanical failure is the second highest grounds for general accidents followed by impacts. Vilchez et al. [106] revealed that mechanical failures contributed 33% of accidents in a survey of 5325 accidents involving hazardous materials. The VVT research [107], found that fire and explosion events occurring in machinery spaces, cargo spaces and accommodation spaces of ships are 79%, 16% and 11% respectively. The influencing factors for mechanical failures (damage to mechanical equipment) are improperly selected material or its aging, extreme conditions of device operation, lack or malfunction of safety devices, bad quality of prepared safety mechanisms, connections or materials, spill of fuel or working fluids, and human error (improper use of tools or machines, negligence of maintenance work, and noncompliance with safety rules) [108]. Similarly, Maleque and Salit [109] outlined that common causes of mechanical failure in a component or system are misuse, assembly errors, manufacturing defects, improper or inadequate maintenance, design errors/deficiencies, improper material or poor selection of materials, improper heat treatments, unforeseen operating conditions, inadequate quality assurance, inadequate environmental protection/control and casting discontinuities.

It is crucial to investigate the most vulnerable areas of any vessel or ship for mechanical failures. Studies of shipping accidents have shown that in most cases the fire originated in the engine room and was caused by oil or fuel coming into contact with hot exhausts. According to a research conducted by Det Norske Veritas (DNV) of 165 fires on board the DNV fleet from 1992 to 1997, 63% of fires occurred in the engine room and 56% of all engine room fires were caused by the combination of oil leakage onto a hot surface [110]. Paula et al. [111] presented the analysis of events involving fire and explosion from the database developed and maintained by Lloyd's Maritime Information Services Limited (LMIS) and found that the majority of fires or explosions are triggered by mechanical failures due to release of fuel oil and/or lube oil system onto hot surfaces in the engine room. This shows that spraying of fuel oil or lube oil on hot surfaces is one of the major causes of fire on board ships. The sources of oil or fuel leakage include damaged flexible hoses, couplings, piston ring, filters and fractured pipes [110].

In several past shipping accidents, various factors have caused mechanical failures and resulted in fires and/or explosions NTSB [112], [113, 114]. For instance, on 10th March 2012, a roll on/roll off vehicle carrier, Alliance Norfolk, encountered rough weather resulting in damaged cargo and subsequent fire. The NTSB [112] determined the probable cause of the fire to be due to ignition of flammable material by an undetermined ignition source due to shifting cargo while the vessel was rolling in heavy seas after losing power.

Another factor responsible for mechanical failure is that of an unsafe act such as failure to use the correct tool and procedure, negligence and inadequate supervision. For example, on 10th December 2009, the containership Maersk Duffield in Moreton Bay, Queensland, Australia caught fire in an engine room. The ATSB investigation [113] found that one or more of the connecting rod palm nuts or counterweight nuts had not been tightened sufficiently during recent overhauls and that the resultant failure of one of the retaining studs was the initiator of the catastrophic engine failure. Similarly, a fire broke out in the auxiliary engine room on board the containership Gunde Maersk on 8th December 2015. The NTSB [115] determined that the fire was caused by fuel leaking from a dislodged O-ring in the fuel supply line and spraying onto the exhaust side of the engine. The leak occurred because the fitting had not been tightened with a torque wrench as prescribed in the manufacturer's written procedures. Likewise, on 13th of July 2014, the bulk carrier Marigold caught fire while loading a cargo of iron ore in Port Hedland, Western Australia. The ATSB [116] determined that the fire began on one of the generators after one of its fuel oil pipe fittings failed, resulting in sprays of fuel oil onto a hot surface on the generator. The investigation found that the compression fitting that failed had been used to connect a replacement pressure gauge that had a different pipe connection fitting size to that of the original pressure gauge. It is evident that human factor is one of the major contributing factors for mechanical failures that lead to fire and explosion in marine vessels.

Use of damaged filter or mechanical seals has been seen as another contributing factor for mechanical failure. For instance, on 19th of March 1999, the Multitank Ascania caught fire due to thermal oil leaking from a thermal oil pump mechanical seal and/or a nearby flange joint onto a pressure relief valve [117]. Similarly, on 11th March 1993, the oil tanker Irving Nordic experienced a main engine crankcase explosion due to piston ring failure contributed to by substantial wear on the cylinder liners and the ignition of lubricating oil [118].

Several mechanical failures occurred due to inadequate maintenances such as failure to follow procedure, inadequate inspection and deficient risk assessment during maintenance. For example, on 3rd February 1995, the Norwegian flagged containership Team Heina caught fire in the engine room due to a spray of hot fuel oil, from a failed compression fitting, onto the fuel rail of the starboard generator engine which was then ignited by the hot exhaust manifold [119]. The ATSB investigation found that the compression fitting failed due to prolonged fretting of the pipe caused by misalignment of the pipe with the fitting and also engine vibration. Similarly, on 9th of February 2007, the Bahamas registered general cargo ship Baltimar Boreas, whilst off Newcastle, New South Wales, caught fire in the engine room due to diesel oil spraying from a failed flexible fuel hose onto the very hot surface of the generator's engine [120]. The investigation found that some hoses were in poor condition and the manufacturer's instruction book and the vessel's safety management system provided no guidance for the maintenance or routine replacement of the flexible hoses. On 24th August 1998, the containership Repulse Bay caught fire in the engine room. The fire was caused by ignition of oil leaked from fractured bolts of the exhaust valve actuator [121]. The bolts fractured due to cyclic loads and fatigue and investigation found that there were no engine manufacturer's guidelines for maintenance or inspection.

Beside these aforementioned factors, there are other factors responsible for mechanical failures including malfunction of automatic controllers, failure of components in safety system and use of defective components. For example, on 2nd of October 2006, failure of the boiler's automatic controller overheated the auxiliary boiler furnace tube, causing a fire to break out on-board the containership Maersk Doha [114]. As a result, the auxiliary boiler fire tube, exhaust gas economiser tubes, uptakes and funnel casing were damaged due to direct, or radiant effect of excessive heat [58].

On marine vessels and offshore structures, corrosion is a leading factor for mechanical failures due to environmental conditions. Corrosion causes material degradation resulting in loss of mechanical properties such as strength and ductility and ultimately causes failure [122]. According to HID Statistics Report (HSR) [123], about 66.3% of hydrocarbon releases were caused by equipment faults during the reported period and the most common cause was ‘mechanical failure’ which, in the majority of cases, was attributed to corrosion or other related degradation.

According to the causes of accidents, it is evident that mechanical failure may not be a standalone cause of a fire and or explosion in a marine vessel, rather it is associated with other contributing factors such as human error, harsh operating and environmental conditions, inadequate maintenance and mechanical fatigue.

2.2.3. Thermal reaction as a cause of fire and explosion accidents

In the shipping industry, reaction or auto-ignition of loaded Hazardous and Noxious Substances (HNS) is a contributing factor for some fire and explosion accidents. According to Munich Re Group [124] report, container vessels can sometimes carry as much as 10-40% volume of hazardous goods. Violent reactions may occur when incompatible chemicals are mixed [125]. Chemical accidents originating from improper storage make up almost 25% of all chemical accidents [126].

In order to avoid potential hazards while mixing or storing chemicals, the guidelines mostly used are from US Environmental Protection Agency’s Chemical Compatibility Chart [127], U.S. Coast Guard’s Cargo Compatibility Chart and Chemical Hazards Response Information System (CHRIS) [128] and National Oceanic and Atmospheric Administration’s Chemical Reactivity Worksheet [129]. Shippers of dangerous goods on board ship are required to pack and mark the goods in accordance with the International Maritime Dangerous Goods (IMDG) Code [130] and to provide necessary shipping documents and declaration that the dangerous goods are in all respects in proper condition for carriage [131].

Despite these guidelines and application of codes, fire and explosion has been reported while shipping dangerous and noxious goods due to chemical reactions or auto-ignition of goods [132-134]. Dangerous and noxious goods on board a ship increase the likelihood and consequences of fire and explosion accidents [135]. This has been supported by some major fire and explosion accidents involving goods carried on board container ships globally [131, 136, 137]. For instance, on 21st March 2006, an explosion and fire on board the container ship Hyundai Fortune in the Indian Ocean compelled the crew to abandon the vessel and it resulted in total constructive loss [133, 136]. It is suspected and alleged that natural ignition of dangerous goods such as calcium hypochlorite or fireworks may have caused the initial explosions due to ambient temperatures and improper stowage [131, 136]. Similarly, on 11th November 2002, the container ship Hanjin Pennsylvania, suffered a fire and explosion in the Indian Ocean with the loss of two lives. This was caused by undeclared dangerous goods, magnesium [138]. These incidents indicate the consequences of undeclared goods in shipping.

The main contributing factors for reaction or auto-ignition of loaded goods are defective packaging and incorrect stowage. The root causes of these are difficulty in chemical hazard identification and human error because of the complex nature of chemistry and the multitude of chemical regulations and their organisations relevant to their packing, storage and shipping [139]. Some chemicals such as methyl ethyl ketone peroxide (MEKP) are unstable and extremely flammable at ambient conditions. They readily cause fire and explosions if they are neither stored nor handled appropriately [140, 141]. On 7th July 2010, a container ship, Charlotte Maersk, caught fire while en route from Port Klang, Malaysia bound for Salalah, Oman. Based on circumstantial evidence, the DMAIB [142] pointed out that the fire probably originated from the container containing methyl ethyl ketone peroxide (MEKP).

Some chemicals such as calcium hypochlorite are prone to thermal runaway, a phenomenon in which the heat naturally produced by the chemical serves to heat itself further, thus generating more heat [143, 144]. According to the United States Court of Appeals for the Second Circuit ruling for the M/V DG Harmony explosion [145], on 9th November 1998, the ship was carrying approximately 160,000 kilograms of calcium hypochlorite below deck when an explosion occurred in the area where the calcium hypochlorite was being stored. Another explosion occurred on the vessel Contship France in October 1997, while the ship was carrying 512 drums of calcium hypochlorite [146]. The explosion was caused by the self-heating of calcium hypochlorite contained in the area of the explosion. The United States Court of Appeals for the Second Circuit [147] acknowledged that temperatures in the cargo area were high enough for the calcium hypochlorite to spontaneously ignite and recognised it as the cause of the explosion.

Additionally, defective packaging, such as loose lids on steel drums and loosely tied or damaged bulky bags can expose HNS goods to hazardous conditions and transporting them in large packages, such as bulky bags, increases the risk of auto-ignition and flammability [148]. Defective packaging and incorrect stowage are directly related to human and organisational errors. For example, on 14th July 2012, the German-flagged full container ship MSC Flaminia caught fire and exploded. The BSU [134] stated, after analysing the physical and chemical properties of all the items of cargo in cargo hatch 4 of the damaged container, the most likely cause of the fire was either a release of car care products or leakage of dimethylaminoethanol from a tank container, which in turn reacted with surrounding items of cargo generating heat and ignition. In February 2007, the Nitrogen, Phosphorous and Potassium (NPK) fertilizer aboard the cargo ship Ostedijk underwent a chemical reaction and destroyed part of the cargo and compromised the ship [149]. This chemical is known to undergo self-sustaining decomposition reactions upon exposure to a heat source [149].

Past shipping accidents confirm that the root causes of chemical reactions that lead to fire and explosion are mainly thermal runaway, auto-ignition and leakage due to defective packaging and incorrect stowage preceded by human and organisational errors, and inadequate safety analysis. This indicates that despite availability of regulatory requirements, databases/tables, codes and signage for chemical storage and handling, thermal reaction is still a major contributing factor to accidents in shipping. This demands a need for detailed study of properties of chemicals and the precautions that should be taken to avoid devastating losses.

2.2.4. Electric fault as a cause of fire and explosion accidents

Faults in electrical systems can be classified into a few groups such as poor electrical connections, short or open circuits, overloads, load imbalance and improper equipment installation [150]. Most commonly, an electrical fault on a ship causes three types of incident, being electrical shock, electrical fires and electrical failures. Electrical fire is a serious hazard aboard any ship and is most likely caused by faulty or improperly maintained electrical equipment. Electrical faults or malfunctions have resulted in several residential, industrial and shipping accidents in the past [151-153]. The National Fire Protection Association research report [154] described electrical fires based on type of device that failed, type of malfunctions, location and origin, and time of occurrence. This report shows that electrical distribution, lighting and power transfer contributed to 57% of reported home fires involving electrical failure or malfunction. Babrauskas [155] described electrical fires by grouping them into two categories, namely (1) according to the nature of the physical mechanism that led to ignition, and (2) according to causative factors which caused the failure mechanism to be triggered. Babrauskas [155] stated that physical mechanisms causing electrical fires are poor connections, arcing across a carbonised path, arcing in air, excessive thermal insulation, overload, ejection of hot particles, dielectric breakdown in solid or liquid insulators and miscellaneous phenomena. The US Consumer Product Safety Commission (CPSC) study [156] outlined the causative factors for electrical fire as improper altercations, improper initial installation, deterioration due to aging, improper use, inadequate capacity, faulty product and unknown. The study found that improper altercations contributed to 37% of the reported residential electrical distribution system fires. Fires on ships are caused by electrical faults, ignition of spilled oils and fuels [157]. A research project on 165 fires on board the DNV fleet from 1992 to 1997 found that 9% of fires originated from electrical components [110].

Electrical faults or malfunctions have caused a number of fire accidents on marine vessels. For instance, on December 11th, 2015 a fire broke out in the electrical control room aboard the freighter Alpena 2015 and resulted in damage costs of 4 million dollars [158]. The NTSB [159] determined that the probable cause of the fire was a fault in the electrical wiring providing power to the aft anchor winch.

In some fire and explosion accidents that occurred on shipping vessels, investigations could not conclusively find actual causes of accidents and thus, only provided likely or possible causes based on circumstances. For instance, on 28th April 1990, Val Rosandra was discharging refrigerated propylene at Brindisi in Italy when a violent explosion occurred in the cargo compressor motor room with a consequent fire due to ignition of escaping propylene. It is believed that the explosion most likely occurred because of ignition of released gas with electrical equipment in the compressor motor room [160]. Similarly, on 7th August 1997, a fire was discovered on the lower bridge deck of the Taiwanese flag bulk carrier Ming Mercy. Based on circumstantial evidence such as the remainder of amateur wiring extensions found in the location of fire and other accommodation spaces, the source of the fire was identified as electrical fault [161].

On 9th of October 2014, a fire started in crew cabin 4 located on the upper deck of Ocean Drover's accommodation block. The investigations [153] could not identify the exact origin or cause of the fire because of loss of physical evidence. However, it was stated that electrical sources or smoking-related activities were likely origins of the fire. On 1st May 2013, heat and smoke were detected on the Swedish-flagged con-ro carrier Atlantic Cartier and the fire spread rapidly, resulting in cargo and material damages, i.e. cable routing beneath the ceiling and deck deformation [162]. Due to preceding extinguishing works, smoke build up and the prolonged period of the fire, traces of evidences about the causes of the fire that might had been presented originally, were covered or destroyed, thus precise causes could not be identified. Based on circumstantial evidence, the BSU Report 99/13 stated that there were a number of conceivable causes, including a technical fault in the electrical system of a vehicle due to an overload or short circuit and partial overheating. Additional possible conceivable causes included negligent or malicious arson, inadequate wiring revealed by cable loops protruding from the protective sheath, traces of corrosion on cables, cable connections of inconsistent strength, existing damage to cables due to welding operations, damage due to abrasion caused by metal cables, forcibly bent cables inside the insulation, damage to the insulation due to overheating and traces of several earlier fires on deck 3B.

Investigation of fire accidents can be complex and not as clear cut as other forms of investigation [163, 164]. This is due to the possibility of omission of traces of evidence because of extinguishing works, smoke build-up, prolonged burning or fire damage, and the complex nature of fire scenarios. Beland [165] claimed that electricity is not as fire prone as generally believed and concluded that electrical fires are conceivable when different abuses such as overloading, combustible materials, high ambient temperatures and inadequate insulation are present. Due to the complexity involved in the justification of actual causes of fire or lack of precise physical evidence, a significant number of fires were mis-investigated and were assigned as electrical fires [165-167]. Beland [165] further argued that electricity is a handy scapegoat because it is often difficult to defend it and electricity, as the cause of fire, is also defended on unconvincing evidence that electrical equipment was close to the point of origin. This later claim is not ruled out if the investigation reports of Atlantic Cartier fire, Ocean Drover fire and Val Rosandra fire and explosion accidents are referred to because their concluding remarks about cause of fire were all based on circumstantial evidence.

Despite such claims, there exists much evidence clearly justifying that electricity has contributed to fire and explosion accidents causing catastrophic consequences in residential, industrial and commercial spaces [152, 166, 168, 169]. This signifies a need for systematic research and investigation approaches in regard to causes of fires and explosions in order to improve accident investigations and to reduce fire and explosion accident losses.

In this study, it is found that about 9% fire and explosion accidents have unknown causes or definite contributing factors, and their underlying causes were not identified during investigation. Most physical evidence leading to fire and explosion is often damaged and destroyed during the accident [163, 164]. This shows that investigation of fire and explosion accidents requires special attention and may need more effective approaches.

2.3. Preventative measures of fire and explosion accidents

The causal factors of fire and explosion accidents can be avoided or mitigated by adopting preventative measures. In order to prevent or mitigate the causes, identification of potential preventative measures is important. However, there is no silver bullet to identify solutions to all contributing factors. Due to this, some potential preventative measures are given in generic ways for each contributing factor.

2.3.1. Prevention and mitigation of human error

Humans are generally seen as error-prone as proved by numerous examples of human error. This signifies a need for design of human independent systems by replacing human performance with technology, specifically by automation, which is considered highly reliable because it is the result of a formal design process and is based on components with known failure rates [170]. Moreover, employing human centred approach may be effective to mitigate human error because it puts the human user at the centre of the design as shown in Figure 2-6 [171].

In marine operations, human errors that lead to fire and or explosion generally occur in maintenance activities. In this study, it is found that 43% of human error results from maintenance related activities such as hot work, overhauls and inspections. Maintenance has been a subject of major interest in order to avoid or reduce human error. Pennie et al. [172] introduced the issue of maintenance error considering the human factor in maritime maintenance and inspection and with emphasis on design for maintainability. Islam et al. [173] determined human error probabilities in maintenance operations of marine engines and argued that the checking of fuel and lubricating oil filter pressure difference activity have high probability for accidents.

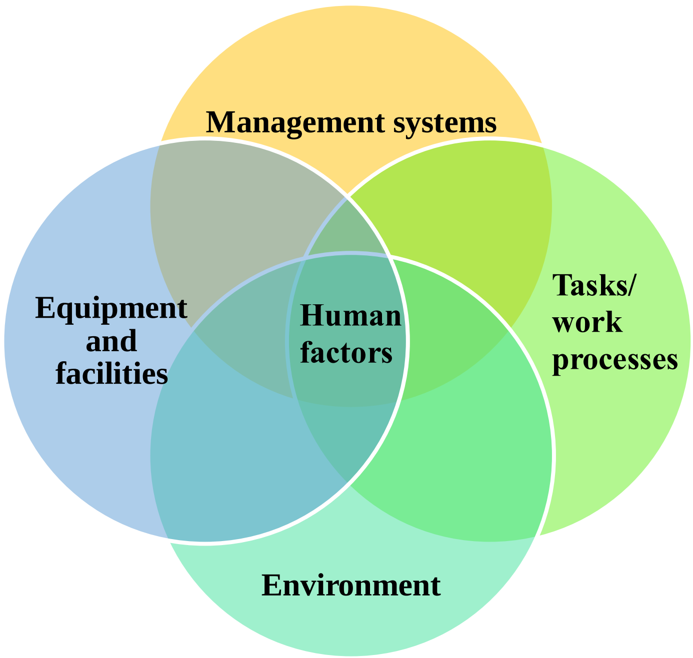

Figure 2-6. Human centred approach for mitigating human error [171].

For human error likelihood assessments, different approaches such as the Human Error Assessment and Reduction Technique (HEART), the Technique for Human Error Rate Prediction (THERP) and the Success Likelihood Index Method (SLIM) are used [174, 175]. Islam et al. [176] developed a monograph for assessing the likelihood of human error in marine operations and argued that the monograph can significantly decrease the time and resources required to estimate Human Error Probability (HEP) when decision making for marine operations involving different environmental and operational conditions. Applications of these methodologies can be helpful tools to reduce the potential of accident occurrence by assessing HEP.

Human error modelling (HEM) and an adoption of 'open culture' or confidential reporting system (CRS) are essential to better understand the causes and effects of human error [87]. The HEM helps to explore the relationship between task and error, and helps to better understand the role of human error in accident sequences. Adoption of open culture encourages employees to report errors that they have made, or seen, so that the underlying causes can be investigated and corrected on time. A CRS enables error or other safety issues to be reported confidentially (without fear of litigation) by an employee to a concerned authority and the authority then communicates the information to the employer for necessary action [177].

In most cases, human errors are caused by the growing imbalance between system reliability and human reliability. In order to overcome this imbalance, the science of ergonomics has evolved which focuses on addressing how the design of the interface between human and machine could take more account of human capabilities and maximize human performance thereby reducing the probability of human error [178]. This helps to prevent human actions becoming out-of-tolerance in terms of exceeding some limit of acceptability for a desired system function [87].

According to Karwowski [179], the current focus of the human factors and ergonomics (HFE) discipline is on the design and management of systems that satisfy human compatibility requirements. The design integration refers to interactions between hardware (computer-based technology), organization (organizational structure), information system and people (human skills, training and expertise). Systems' management maintains the interactions between various systems' elements across process and product quality, workplace and work system design, occupational safety and health programmes and corporate environmental protection policies. The author further emphasised that emerging branches of HFE such as microergonomics, neuro-ergonomics and nanoergonomics would play a significant role in mitigating human errors. For instance, neuro-ergonomics focuses on the neural control and brain manifestations of the perceptual-physical-cognitive-emotional interrelationships in human work activities [180]. This aims to design a workplace to better match the neural capacities and limitations of human.

The ABS [181] proposed a Human Factors Engineering/Ergonomics Model which contains four elements that influence safety and efficiency in job performance. They are vessel or offshore installation design and layout considerations, workplace ambient environmental conditions, management and organizational issues related to operations, and the personnel who operate the vessel or offshore installation as depicted in Figure 2-7. In order to maintain safety, productivity and efficiency, sufficient attention needs to be given to these elements and these elements should be at the core of any HFE implementation effort (ABS, 2014).

People is an integral part of organisation and system as discussed in section 2.2.1. For prevention of both active and latent human failures, it should be looked at from a system approach which generally consists of defences, barriers, and safeguards. Maritime transportation has many defensive layers such as those which are engineered (alarms, physical barriers, automatic shutdowns, etc), people (control room operators, etc), and procedures and administrative controls. For prevention of fire and explosion accidents due to human factor, Swiss cheese model can be used as suggested by Reason [88]. The developed Swiss cheese model has three safety layers, equipment, processes and people, with direct influence of organisational safety culture as shown in Figure 2-8. The presence of holes (errors, deficiency, flaws) in any one layer does not normally cause an accident. Usually, this can happen only when the holes in all layers momentarily line up allowing the hazards to pass through all layers. It is obvious that reducing the number of holes in each slice would play a key role in decreasing likelihood of accidents.

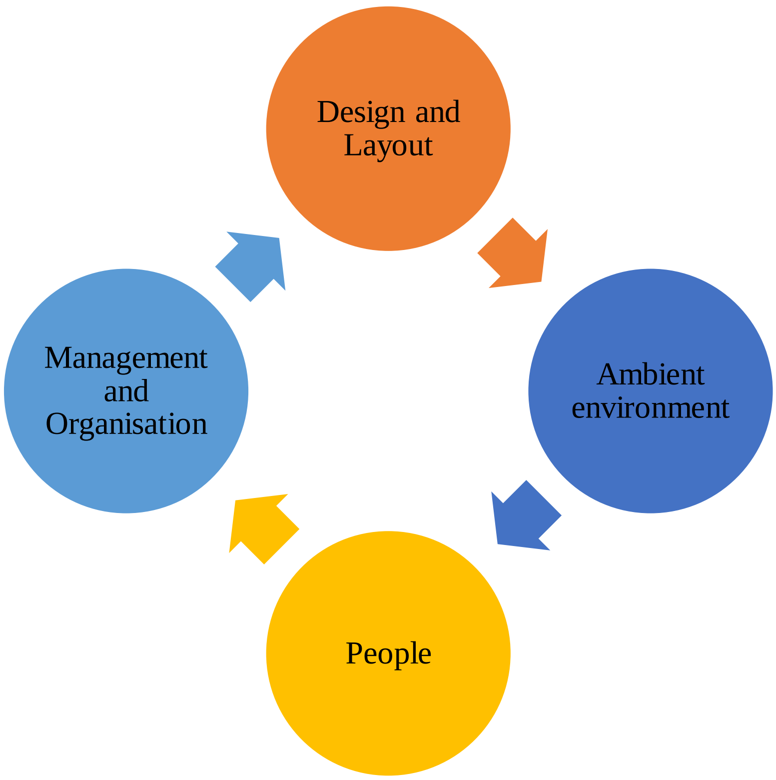

Figure 2-7. ABS Human Factors Engineering/Ergonomics Model

Equipment should be designed, located and modified in such a way that it contributes in reduction of errors during use, maintenance, inspection and testing thereby incorporating the effects of the environment in which they are operated. Workspace should be designed suitable for high human reliability. As far as possible equipment and its accessories need to be equipped with fire resistances and protections and flammable fluid inventories should have adequate leak prevention measures.

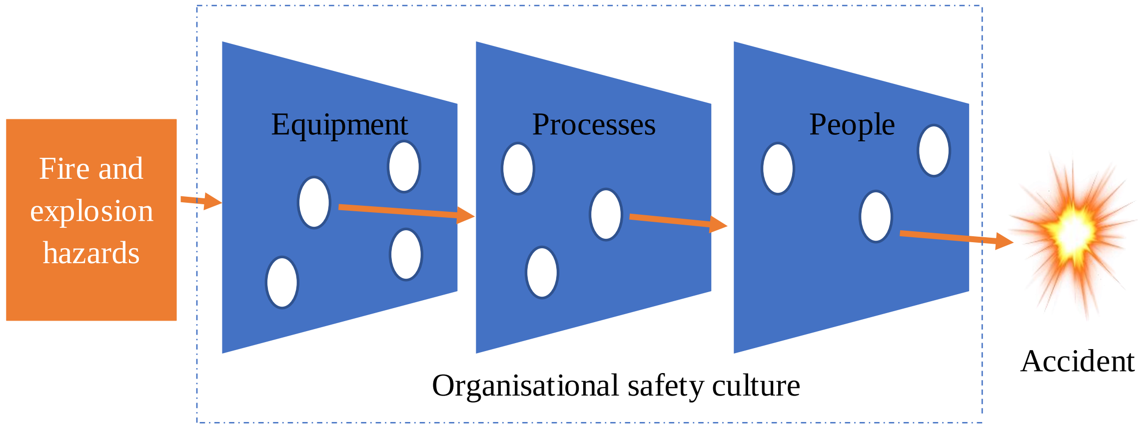

Figure 2-8. Swiss cheese model for accident prevention due to human factor

Second safety barrier is processes which mainly comprise procedures, fire and explosion risk management, near misses and precursor's investigations, safety critical communication, staffing levels and workload. Procedures need to be clear and practical. Safety critical communications must be clear and unambiguous. Staffing levels and workloads must not compromise safety. The final barrier is people. Employees need adequate training and competence along with the correct level of supervision and leadership. Appropriate instructions for various operations (hot work permits, inspection and maintenance procedures, flammable gas monitoring) should be made available. Safety analysis should include human failures and behavioural safety including human interactions with other factors. Organisational safety culture needs to be appropriate such that it can play a central role to organise and co-ordinate safety barriers for prevention of accidents.

2.3.2. Prevention and mitigation of mechanical failure

Mechanical failures involve an extremely complex interaction of load, time and environment [182]. The complex nature of metal failures can only be understood by identifying different types of mechanical failures such as fracture, fatigue, creep, corrosion and wear [109]. Vilchez *et al.* [106] identified that leaking valve, overpressure, metallurgy failure, corrosion, flange coupling failure, hose failure, overheating, weld failure, leaking gland, relief valve failure, fatigue, overload, brittle failure, incompatible material use are specific causes of mechanical failure.

The causes of fatigue failure are identified as unintended stresses, misuse, design deficiencies, incorrect assembly, and deficient testing and inspection techniques [183]. In this study, fatigue failure of a component is observed in 36% of accidents in mechanical failure category. Failure due to fracture can be prevented by avoiding stress concentration, reducing the speed of loading, avoiding ductile-brittle transition temperature and preventing thermal shock [109]. The most effective method to prevent fatigue failure is in design improvement by avoiding sharp surface tears, surface discontinuities and tensile residual stresses and improving fabrication and fastening procedures [184]. Creep occurs when the metal, under certain loads is heated normally over 40% of melting temperature of the material [185]. An understanding of behaviour of a material at high temperature with certain load over a period of time is a useful approach. It helps in evaluating failures of components due to creep [186]. The fatigue failure and creep can be prevented by avoiding unintended stresses and strains and design deficiencies and using adequate coating, defect detection and testing techniques.

Corrosion is a very widespread problem in all engineering structures, especially those in harsh chemical environments such as chemical engineering processing equipment and in salty environments [186]. Failure, due to corrosion, can be controlled or minimised by various means, such as correct material selection, galvanic protection, corrosion inhibitors, adequate corrosion monitoring and inspection and protective coating [187]. The various environmental conditions usually encountered by anticorrosive coatings are given in Figure 2-9. In order to avoid material degradation due to corrosion, protection of anticorrosive coatings is essential. Anticorrosive coatings used in metals can be protected using barrier protection, passivation of surface (inhibitive effect) and sacrificial protection (galvanic effect) [188]. Additionally, adoption of risk based inspection planning and integrity assessment methods may avoid failures due to material degradation [189].

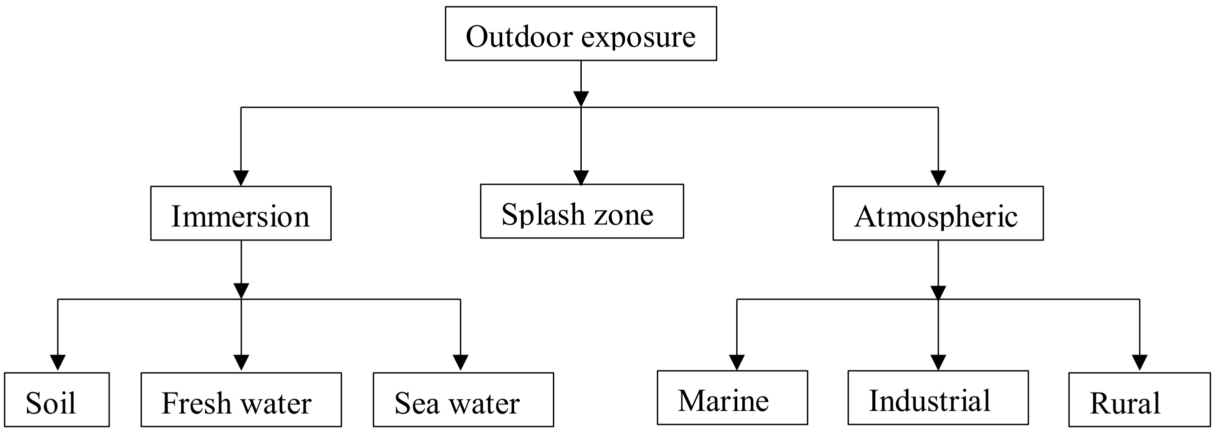

Figure 2-9. Various environments encountered by anticorrosive coatings [188].

It is important to understand the principles of corrosion in order to effectively select materials and to design, fabricate, and utilize metal structures for the optimum economic life of facilities because no particular material is the cure for all types of corrosion [122]. To understand the principles of corrosion, modelling of corrosion has been done considering experimental tests and probabilistic approaches such as Bayesian Networks (BN) [190, 191]. The Energy Institute [192] proposed guidance model for improving corrosion management practices in oil and gas production and processing as shown in Figure 2-10.

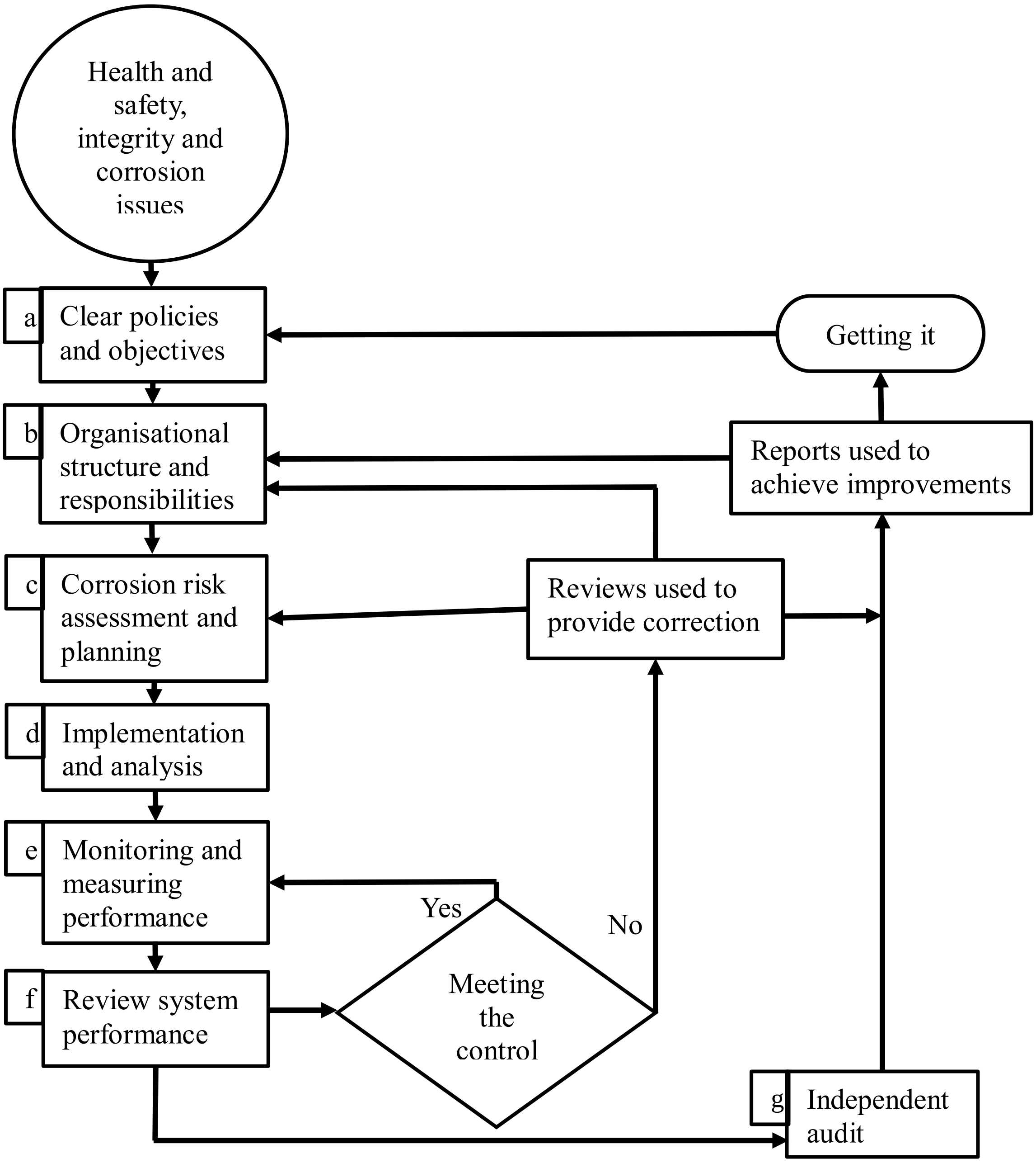

Figure 2-10. The basic corrosion management process model [192]

Wear is caused by the removal or displacement of material due to mechanical action of a contacting solid, liquid or gas. Failure due to wear can be controlled by preventing removal of material and reduction of dimension with proper material selection and design [184]. Moreover, materials or parts vulnerable to wear need adequate maintenance and overhaul because wear cannot be totally eliminated. Therefore, the causes of failure of engineering components can be controlled or prevented by appropriate design, better materials selection, avoiding manufacturing defects and overloading, and adequate maintenance.

2.3.3. Prevention of thermal reaction in shipped goods

The shipping industry is involved with transporting goods ranging from non-hazardous to water reactive, corrosive, toxic and highly flammable. For maintaining safety during the transportation of hazardous goods, a number of international codes, such as international maritime dangerous goods code, construction and equipment of ships carrying dangerous chemicals in bulk (resolution A212 VII), Marine pollution convention, the revised guidelines of IMCO on hazardous chemical classification and the International Convention for the Safety of Life at Sea (SOLAS) Chapter VII (Carriage of Dangerous Goods) amendments (2002), are being implemented [193]. Goods that are listed within the codes must be transported according to the provisions which specify requirements for packing, consignment, and transport operations, including packaging to be used, marking, labelling, placarding, stowing, segregation, and transport documentation [138]. Despite these codes and regulations, the shipping industry has experienced many fire and explosion accidents in the past, mainly because of thermal runaway, auto-ignition and leakage due to defective packaging and incorrect stowage.

Some chemicals decompose rapidly on heating and under influence of light, and react violently with incompatible substances or ignition sources (acids, bases, reducing agents and heavy metals) to cause fire and explosion hazards [194]. These properties of chemicals are required to be clearly identified, and more efforts are needed for reactive, self-reactive or incompatible chemicals. For instance, Wang *et al.* [194] used a preliminary calorimetry approach to identify the effect of the incompatibility on the thermal hazards of Tert-butyl hydroperoxide (TBHP) to understand the safe design and precaution for the hazards of incompatibility of TBHP. The study found that TBHP solutions with alkaline have potential thermal instability and the aqueous TBHP can show more severe thermal and self-reactive hazards in the presence of contaminants. Hence, care should be taken in shipping, handling and storing. Due to this, Wang and Shu [195] recommended reconsideration of the classification of thermal hazards of organic peroxide from the viewpoint of a proactive approach to an intrinsically safer design by incorporating safer process operating conditions, type and material of storage tanks for transportation, and firefighting via temperature control and pressure relief systems.

Thermal runaway is another contributing factor for fire and explosion accident. Gustin [196] provided the case studies of thermal runaway reactions and stated that the study of accident case histories can greatly reduce the rate of occurrence of runaway reaction accidents. Similarly, Ho et al. [197] analysed 65 incidents of runaway reactions and emergency relief in Taiwan and classified them into several categories according to their causes, material involved, equipment types, reaction types and ignition sources. The study found that heat of reaction was the main cause in initiating thermal or pressure runaway.

Chemicals with National Fire Protection Association (NFPA) reactivity ratings of 2 and above can be categorized as reactive and can undergo runaway reactions, decompositions, or self-polymerizations with resulting temperature or pressure increase [193]. Hence, these chemicals should be stored or handled appropriately avoiding hazardous environments.

For safe handling of HNS, containerized cargo handling is gaining popularity. This has led to the design of various containers suited to hazardous substances. For instance, an insulated storage system with balanced thermal energy flow [198] and shipping and storage system for exothermic materials [199] can be a better solution to mitigate thermal runaway and decomposition hazards of chemicals. Moreover, the specialised containers may prevent leakage and defective packaging. However, the container's contents need to be properly secured and braced.

Simmons *et al.* [139] compared the chemical incident reports of the U.S Department of Energy (May 2005) and U.S. Chemical Safety Board [126] and argued that in both reports about 70% of chemicals involved in incidents were either not regulated or had NFPA instability rating of "0" or "1". Moreover, not all chemicals are rated and the NFPA rating system cannot be used for hazard identification of unrated chemicals. Likewise, Process Safety Management (PSM) regulation is not all-inclusive indicating that it does not regulate all chemicals. This indicates a need for more extensive hazard analysis approaches and more robust regulations.

Undeclared dangerous goods that entered the transport chain as a result of awareness, lack of regulations, mistakes/omissions during cargo transport booking, and deliberate non-declaration have caused a number of fire and explosion accidents. More extensive incident and inspection data is required to estimate the rates of undeclared dangerous goods and develop quantitative frequencies for the model [138]. All stakeholders in the transport chain, such as manufacturers, shippers, cargo brokers, freight forwarders and freight consolidators should be more accountable for ensuring that dangerous goods are correctly and honestly declared [200]. Furthermore, appropriate training should be given to crew and personnel about regulations, precautions and packaging procedures in relation to handling and transporting dangerous goods. Simmons *et al.* [139] proposed that academia, industry, and government join together and establish training and experience requirements to remedy risk of chemical hazards.

2.3.4. Prevention of electrical faults

In marine operations, electrical faults are caused by several factors, as discussed in section 2.4. Prevention of these causes is essential because a simple fault can be catastrophic in ships. For instance, a minor electrical spark may be an ignition source for an extreme fire and explosion event. Arcing fault is a common cause of electrical fires. Due to high-impedance, currents frequently fall within the range of normal working loads during arcing faults. Under this condition, circuit breakers frequently become ineffective against arcing faults [201]. The use of arc-resistant switchboards and the use of arc-fault detection systems such as automatic arc-fault protection can significantly reduce the risk to personnel when arcing occurs [202].

The ignition from poor connections (overheating or glowing connections) and external heating resulting in short circuit or arcing can be prevented by ensuring proper training to crew and fail-safe design of the system. Physical damage, voltage surges and deterioration of electrical insulation present hazards which can cause electrical fires and further research is required for physical mechanisms, minimum values, time frame for ignition, industrial fires and metallurgical issues relating to electrical fires [155]. Avoiding the use of defective or faulty electrical appliances may prevent short circuit ignitions. Moreover, very minor incidents such as static electricity, electric spark and arc can be sufficient to ignite accumulated combustible gas in confined or semi-confined areas and avoiding their sources will reduce likelihood of fire and explosion events.

Skjong et al. [203] stated that characterization of the marine vessel electrical grid through real-time measurements, and the monitoring of fundamental parameters such as impedance, harmonic currents and voltages, would be essential to ensure the safety, integrity, and stability of the marine vessel power system. Since the intensive trend in use of electricity, the authors proposed that a smart grid similar to the modern land-based electrical system should be a necessity in marine vessels.

Using recent technologies, such as infrared thermography (IRT) in condition monitoring and inspection techniques, can enable identification of the presence of any thermal anomalies in electrical appliances [150]. The rapid development of computer programs, sensor, and signal processing technologies, and integration with artificial intelligence (AI) techniques, has made it possible to implement fault diagnosis and prognosis effectively [204]. Previous researchers stated that the use of AI software agents will become essential for monitoring, diagnosing, and predicting system equipment faults, particularly important to critical systems and components such as engines, power generation, and thermal management.

For a fire to occur there must be the three basic components forming the fire triangle, oxidizer, flammable material and a source of thermal energy. These factors combined together result in the spread of fire and often lead to tragic consequences. In order to avoid or control a fire, one of these factors should be avoided. Investigating the root causes of the previous accidents reveals that the fuel leakage is the consequence of different fire and explosion accidents occurring in the engine rooms [116, 120, 121]. In a ship, fire occurs mostly in the engine room due to the high chance of having all three factors simultaneously. Air (oxygen) and hot surfaces exist constantly in the engine room. When fuel or lubricant oil sprays on hot surfaces, there is high chance of a fire and explosion event due to the high flammability of conventional fuel or oil. Several questions such as ‘are there alternative fuels with less flammable property?’ and ‘does employing less flammable fuels or oils reduce the likelihood of fire and explosion events?’ can be raised.

2.4. Alternative fuels

In this study, it is found that 31% fire and explosion accidents are caused by an accidental release of fuel or lubricating oil in the engine room. Replacing these highly flammable materials with other less flammable fuels may help to reduce the risk of ignition during accidental leakage. In the quest for less hazardous fuels, effectiveness of alternative fuels needs to be reviewed from safety perspectives. According to DNV report [31], alternative fuels that are already used or could potentially be used in shipping in the future include LNG, Liquefied Petroleum Gas (LPG), biofuels, synthetic fuels (Fisher-Tropsch) [32], methanol and ethanol, Di-Methyl Ether (DME), biogas, hydrogen, biodiesel nuclear fuel and use of electricity for charging batteries and cold ironing. The EMSA report (2017) states that the currently considered alternative fuels in shipping such as LNG, electricity, biodiesel, and methanol and other fuels such as LPG, ethanol, DME, biogas, synthetic fuels, hydrogen (particularly for use in fuel cells), and nuclear fuel, could play a role in the future.

When analysing the viability and prospect of adoption of alternative fuels for use in shipping, safety considerations also need to be taken into account particularly the risks of fire and explosion accidents. In order to prevent or mitigate fire and explosion accidents in shipping, the effectiveness of alternative fuels needs to be assessed. The differences in chemistry and physical properties lead to different risks associated with transferring, dispensing, and handling alternative fuels. According to the EMSA [205], one common challenge posed by the adoption of most alternative fuels is their physical and chemical characteristics, typically associated with low flashpoints, higher volatilities, different energy content per unit mass and in some cases toxicity.

In the current study, only fire and explosion related hazards that could be posed by alternative fuels are discussed. Inherently, all fuels present fire and explosion hazards if they are not stored or handled appropriately. Astbury [206] explained the ignition and combustion properties of alternative fuels in relation to fire and explosion hazards such as gross calorific value, octane number, flash point, flammable limits, auto-ignition temperature, electrical resistivity, minimum ignition energy, boiling point and water solubility. A summary of ignition and combustion properties of some proposed alternative fuels is given in Table 2-2. The author stated that most alternative fuels have similar ignition and combustion characteristics as existing known conventional fuels except hydrogen, and additional hazards posed by alternative fuels are manageable. The author further stated that the use of many alternative fuels requires some adjustment or substitution of minor parts of existing burner or engine designs to allow for direct substitution of traditional fuels. If this adjustment or substitution does not occur properly, the alternative fuel may not be used or likely becomes uneconomical and or presents more hazards. Maggio et al. [207] stated that alternative fuels do not present greater risks than conventional fuels, however their risks are simply different. Thus, with proper training, facility design and adequate precautions, alternative fuels can be handled safely.

Table 2-2. Ignition and combustion properties of some alternative fuels (Adopted from [206]).

Material	**Gross Calorific Value (MJ/kg)**	**Octane number**	**Flash point (°C)**	**Flammable limits (%,v/v)**	**Auto ignition temperature (°C)**	**Resistivity (Ωm)**	**Minimum Ignition Energy (mJ)**
Ethanol	29.73	100	13	3.3-19	363	7.4×10^6	f
Methanol	22.72	99	11	6-36	385	3×10^3	0.14
LNG	19.98	>100	-188	5-15	537	Gas	0.28
CNG	19.98	120	Gas	5-15	537	N/A	0.28
LPG (Propane)	50.49	104	Gas	2.1-9.5	450	Gas	0.25
LH_2	158.9	f	Gas	4-75	500	10^{17}	0.017
Hydrogen	158.9	f	Gas	4-75	500	N/A	0.017

f = No data available

The ignition and combustion properties of biodiesel are the same as those of conventional hydrocarbon oil-based diesel fuel, but it is a lower fire and explosion hazard than standard diesel because of a higher flash point. These properties make biodiesel and its blends with petroleum diesel safer to store, handle and use than conventional diesel fuel.

Methanol has a low rate of evaporation and low radiant heat energy which makes it a safer fuel because it is less likely to ignite in accidents and less harmful to people when it does [208]. Moreover, methanol is much less likely than gasoline to ignite in open air (well-ventilated areas) due to its low volatility. Methanol in a closed tank should be considered an explosion hazard because methanol fuel-air mixture in closed air tanks is within its ignition limits [207]. However, in the case of spontaneous combustion, methanol is classified between gasoline and diesel fuel [209]. Additionally, due to the lower volatility and higher flammable limit, pure methanol (M100) is projected to result in as much as a 90 percent reduction in the number of automotive fuel related fires compared to gasoline [210]. According to Fort [211], METHAPU project has successfully demonstrated that the on-deck methanol tank and fuel cell system did not present any greater risk to the ship, occupants, or environment than that associated with conventional fuels. Risk assessments are carried out in Stena Germanica, SPIRETH project and Waterfront Shipping chemical tanker and were approved for installation, demonstrating that safety considerations are not a barrier to the use of methanol fuel systems on ships [212]. Similar to methanol, ethanol fires are less hazardous than gasoline and they can be readily extinguished with water [213]. It is safer than gasoline to store, transport and refuel [214]. Thus, ethanol also presents a moderate fire and explosion hazard if handled incorrectly.

The main hazard related to CNG is gross leakage from the fuel feed pipe work. The potential for ignition immediately after the accident (leakages) is greater for CNG than petrol as the flammable atmosphere will be far greater and likely to spread further and more quickly [206]. However, natural gas is safer than gasoline and diesel in many respects such as its ignition temperature is higher than gasoline and diesel and it is more difficult to ignite accidentally in comparison to both [215]. Additionally, it is lighter than air and any leaks disperse rapidly upwards while gasoline and diesel pool on the ground, increasing the danger of fire [216]. Thus, natural gas presents fewer fire or explosion hazards in well ventilated areas because of high auto-ignition temperature and narrow explosive range.

LNG as a liquid is neither flammable nor explosive, but its vapour ignites when the vapour-air mixture is 5-15% [217]. Fire and or explosion hazards related to LNG are similar to CNG though other hazards are different, for example, LNG has roll-over and cryogenic hazards. Use of LNG as an alternative fuel is promising and has the possibility of being a leading option in order to retain a substantial share of the world bunker market because it is proven technology (about 40 ships are currently running on LNG), and is meeting more than new emissions requirements and has less CO_2 emissions [218]. Moreover, LNG is already providing an economic alternative to diesel in the heavy duty trucking industry, in port facility vehicles, and increasingly in marine and rail applications [219, 220]. Thus, similar to any flammable substance, appropriate design, regulations and personnel training are needed to maintain a safe environment for application of LNG as a fuel.

LPG is highly flammable and its leakage from a fractured pipe would form a large persistent flammable atmosphere, which would likely ignite [206]. As it is heavier than air, it tends to settle in trenches or maintenance pits increasing explosion hazards. Leak prevention measure is key to mitigating these hazards.

Hydrogen has a much lower minimum ignition energy (0.017 mJ) than any traditional hydrocarbon fuel and makes it far more sensitive to ignition than any other gaseous fuel [206]. Moreover, hydrogen has a much higher flame speed than any other gas and has wider flammable limits (4-75%) with higher explosion hazards [206]. Hydrogen ignition related accidents have occurred in the past resulting in severe consequences [221]. Additional hazards may depend on its production and storage types.

This shows that there are certain properties which make some fuels more or less hazardous than others and the severity of risks posed by each alternative fuel may not be the same. In order to mitigate the fire and or explosion hazards of alternative fuels for commercial applications, necessary precaution measures should be put in place with appropriate fail-safe designs and their cost effectiveness needs to be assessed.

Existing studies on alternative fuels in shipping are mostly focussed on the possibility of emission reductions, however, secondary effects because of emission reduction measures are not extensively studied. Luo [222] identified 8 possible side effects of emissions reduction measures, including both positive and negative impacts on emission reduction, world trade, economic efficiency, and the local environment. Maddox consulting [223], identified 13 measures that have a negative marginal abatement cost (MAC) on emissions reduction in shipping, and analysed the six categories of barriers to their successful implementation, including technological, operational (or physical), regulatory, economic, market failure, and administrative barriers. Most cost effectiveness of alternative fuels is mainly assessed in relation to greenhouse gas reduction measures and not much emphasis is given to fire and explosion hazard reduction measures [224, 225]. Grahn et al. [226], analysed cost effectiveness of LNG, fuel cells, hydrogen, synthetic fuels (gas-to-liquid (GTL)) and biofuel using the Global Energy Transition model (GET-RC 6.2). This was conducted based on global energy system modelling aiming to analyse fuel choices in the shipping sector under stringent Carbon dioxide (CO_2) constraints and reached the following conclusions;

1. A transition from oil-based fuels to an alternative fuel could be cost-effective in the next 10-20 years,
2. LNG could be a major fuel in the shipping sector between 2020 and 2070, depending on the cost of the storage tank,
3. After 2070, a variety of fuels; hydrogen, synthetic fuels and biofuels will be chosen depending on the characteristic of the ship,
4. Time of transition and fuel choices are affected by the chosen target of CO_2 concentration, energy demand scenarios and the total supply of oil and natural gas.

Findings of another study conducted by Taljegard et al. [227] support these conclusions and state that (i) it is cost-effective to start the phase out of fuel oil within the shipping sector in the next decade; (ii) natural gas based fuels (liquefied natural gas and methanol) are the most probable substitutes during the study period; (iii) availability of carbon capture and storage (CCS), the CO_2 target, the liquefied natural gas tank cost and potential oil resources affect marine fuel choices significantly; and (iv) biofuels rarely play a major role in the shipping sector, due to limited supply and competition for bioenergy from other energy sectors. However, neither study incorporated all variables nor uncertainties such as engine efficiency, regulatory impact and cost of technology replacement or modification because some of the technologies are not yet commercial. This shows that there is a need for analysing cost effectiveness from safety perspective of alternative fuels incorporating adequate parameters in sensitivity analysis.

Regardless of inherent hazards and many uncertainties such as availability, cost and technology, some alternative fuels are already being used in marine vessels as a prime mover. Examples of marine vessels running on alternative fuels are (1) MS Bergensfjord (LNG fuelled RO-PAX), (2) Viking Lady (LNG Fuelled, also demonstrator project for Fuels Cells in the context of the FellowSHIP project) and (3) MV Stena Germanica (First Methanol fuelled ship conversion) (EMSA, 2017).

The proposed alternative fuels have both advantages and disadvantages at this stage in relation to fire and or explosion hazards and would demand further research in many aspects. Due to this, it is highly unlikely that any single technology or fuel has the potential to be the ‘‘silver bullet’’ to be able to meet energy challenge and security, and mitigate the effects of climate change and other harmful environmental impacts, because all the options are subject to constraints of some kind [228].

From the initial stage of the development of alternative fuels and technologies, the consideration of fire and explosion hazard mitigation measures could play a significant role in reducing fire and explosion accidents in shipping. Comparing flammability properties of potential alternative fuels, some alternative fuels have favourable and safer properties than traditional fuels, which certainly minimise the risks of fire and explosion if adequate precautions are adopted.

2.5. Conclusions

Fire and explosion accidents are reported as a common accident type in maritime transportation. Fire and explosion accidents that occurred in maritime transportation between 1990 and 2015 are reviewed and analysed in order to identify causal and underlying causes of these accidents. The causal factors of fire and explosion accidents are identified and categorised as human error, thermal reaction, electrical fault, mechanical failures and unknown.

The general causes of fire and explosion accidents in shipping show that human error is the most common contributing factor accounting for 48% of accidents. In most cases, it is found that skill-based error, inadequate supervision and inadequate organisational processes have resulted in mechanical failures, chemical reactions and electrical fault. Moreover, it is found that 43% of human error is arose from maintenance related activities. HEM, better safety culture, design integration and system management, and neuro-ergonomics design are seen as some key approaches in managing human failure.

In this study, it is found that mechanical failure contributed to 22% of fire and explosion accidents. Deficient maintenance activity and inappropriate overhauls have been the main contributors to leakage and mechanical failure. Mechanical failure can be prevented by controlling corrosion, fatigue failure, and wear and creep which are further mitigated by adequate design and safety systems. Investigations of shipping accidents have shown that in most cases fire originated in the engine room and was caused by leakage of oil or fuel coming into contact with hot exhausts. It is suggested that the failure of engineering components can be controlled or prevented by proper design, better materials selection, avoiding manufacturing defects and overloading, and adequate maintenance.

Hot metal surfaces, static electricity and electrical sparks and arcs are the major sources of ignition causing fire and explosion. In this study, about 7% of accidents are found to be caused by electrical fires. The main contributing factors for electrical fires are improper altercations, improper initial installation, and deterioration due to aging, improper use, inadequate capacity and faulty product. Some studies claimed that investigators considered a fire as electrical without definite evidence which led to the ruling out of other potential causes. Because of the complexity involved in investigation of fires, most fire accidents discussed in this paper are considered as electrical fires based on circumstantial evidences. Uses of arc-resistant switchboards and arc-fault detection systems such as automatic arc-fault protection can significantly reduce the risks of fire and shock. Moreover, application of smart grid similar to the modern land-based electrical system would help to better manage the electrical system in ships. It has been proposed that using recent technologies such as infrared thermography and AI in condition monitoring and inspection techniques may enable identification of the presence of any anomalies in electrical appliances or systems.

Thermal reaction has contributed 14% to fire and explosion accidents, and breach of guidelines or policies was found to be the main root cause of accident. Defective packaging, inadequate hazard identification and incorrect stowage have contributed to accidents in shipping.

Additionally, undeclared dangerous goods due to lack of awareness of regulations, mistakes or omissions during cargo transport booking, and deliberate non-declaration, are also significant contributors to shipping accidents. In order to mitigate fire and or explosion from reaction, a robust and extensive hazard identification procedure or tool is needed and all stakeholders, including manufacturers and those involved in a transport chain, should be accountable for safe handling of commodities. Adequate safety analysis and effective training and education are found to be common recommendation in most accidents caused by thermal reaction. Moreover, it is found that in 9% of accidents, investigators could not conclusively identify causes of accidents. This shows that accident investigation may need more rigorous approaches and experts.

All fuels are prone to fire and or explosion risks, however, some fuels are less prone to risk of fire and explosion because of differences in flammability and combustion properties. In order to compare the fire and explosion hazards posed by different fuels, properties of some proposed alternative fuels are compared, and it is found that at this stage, adoption of alternative fuels do not pose higher fire and explosion risks than conventional fuels. LNG, CNG and methanol have suitable properties for mitigating fire and explosion hazards and appropriate management of their hazards could be safer than traditional fuels. The proposed alternative fuels have weaknesses and strengths in relation to fire and or explosion hazards and demands further studies in many aspects. Due to the lack of adequate studies and technological immaturity, at this stage, it is highly unlikely that any single alternative fuel has the potential to be able to mitigate fire and explosion risks, to meet energy challenge and security, and to mitigate the effects of climate change.

Chapter 3

Aging and Failure Analysis of LNG Spill on Steel Structure in Congested Marine Offshore Facility

Abstract

The cryogenic temperature of LNG induces unexpected thermal stress on a metallic structure when LNG comes in contact with it. The induced thermal stress may combine with other operational stress causing the system to face abnormally high stress rates. Furthermore, small cracks, imperfections or design flaws can propagate at high rate under the new increased stress condition. This may lead to catastrophic failure of the structure. In this study, a methodology is proposed for the assessment of the impact of a fugitive LNG spill on a typical steel structure. The study outlines an insight into the structural integrity assessment of the structure during an LNG spill. The focus of the study is to model an LNG pool formation in a complex offshore structure using Flame Acceleration Simulator (FLACS), and to analyse the temperature profile of the pool using thermal analysis. The thermal stress obtained from the transient analysis is considered as a load for LNG spill impact assessment. Ten different semi-elliptical crack sizes are considered to analyse the impact of thermal stress on crack propagation. The outcome of this study reveals that the fugitive release of LNG does not cause immediate crack propagation, however, it has a significant impact on the operational life of the structure. This study confirms that the fugitive release of LNG is a serious hazard for structural integrity and demands effective preventive and/or control measures.

Keywords: LNG spill, FLACS, finite element analysis, crack propagation, fatigue failure

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3.1. Introduction

At low temperatures, materials tend to become brittle [229]. Low temperatures can affect materials by causing embrittlement and also inducing unwanted stresses either as a result of the thermal contraction or thermal gradients within a structure [43]. Most structures designed and constructed to operate in low temperature systems are fabricated at room temperature. One of the major concerns is the effect of the differential thermal contraction and associated thermal stress posed by low temperature when two dissimilar materials are bonded together [45]. Thus, it is of considerable importance to understand this behaviour of materials. Many factors can contribute to the brittle fracture of a structure including temperature, material toughness, flaws, exposure to fatigue and geometric configuration [47]. When structural materials lose ductility or become abruptly brittle, they can break suddenly and unexpectedly under normal or increased stress conditions [230]. This is due to ductile to brittle transition behaviour caused by low temperature. The ductile to brittle transition is characterized by a sudden and significant drop in the energy absorbed by a metal subjected to impact loading [231]. As temperature decreases, metal's ability to absorb energy decreases. At low temperatures the ductility may suddenly decrease to almost zero. This temperature is called the Nil-Ductility Transition Temperature (NDTT).

In the past, cold brittleness had caused breakup of ships in cold ocean water. For instance, sinking of the Titanic was caused primarily by the brittleness of the steel used to construct its hull and rivets [232]. It is believed that the steel was below the ductile to brittle transition temperature in the icy water of the Atlantic Ocean and the collision with an iceberg resulted in brittle fracture of the bolts that were joining the steel plates together [233]. Because of this, understanding the potential impact of very low temperature on structure is important for safety and structural integrity of the facility.

The production, transportation and use of LNG have all been increasing steadily and globally [234]. A controlled venting of cryogenic vapours (LNG) from storage is usually not hazardous. However, an accidental release of LNG from a processing system under pressure (mainly in Floating LNG facility and LNG ship) can give rise to serious hazards [43, 235]. LNG spill can cause embrittlement of structure, fire, explosion, freeze burns, rollover, and asphyxiation [15]. Several studies [50, 51, 236, 237] have considered hazards related to fire and explosion in LNG processing facilities. The hazard posed by cryogenic temperature of LNG to structural integrity is also key to risk assessment in an LNG processing facility. The typical temperature of LNG at atmospheric pressure is -162 °C which is much lower than the ductile to brittle transition temperature of common structural materials [15]. Contact of steel with cryogenic fluids is known to cause embrittlement, which can significantly reduce the strength of the steel [238]. Due to the complex nature of LNG, the US Government Accountability Office (GAO) commissioned a study on the current state of knowledge of the relevant issues/phenomenon [239]. One of the recommendations of this study was to improve the state of knowledge surrounding the potential for cascading damage to LNG vessels during an unintended LNG spill. Accidental contact by LNG on structure has been responsible for causing various accidents. A list of LNG spillage incidents that have resulted in structural cracking or fractures is provided in Table 3-1.

Table 3-1. Structural damages resulting from LNG contact [15, 240, 241].

Incident year	Ship/facility name (Location)	Cause	Operation status	Consequence	
				Injuries fatalities	Ship/property damage
1944	East Ohio Gas LNG tank (Cleveland)	Tank failure	storage	128 deaths, 200 injuries	NA
1965	Methane Princess	Valve leakage	Disconnecting after discharge	No	Deck fractures
1965	Jules Vernet	Overfilling	Loading	No	Tank cover and deck fractures
1966	Methane Princess		NA		Cargo leakage reported.
1971	LNG ship Esso Brega, LaSpezia LNG import Terminal (Italy)	Rollover incident due to sudden pressure build-up in the tank	Unloading LNG into the storage tank	NA	LNG vapor discharged from tank safety valve and vents, tank roof slightly damaged.
1973	(Canvey Island, UK)		NA	No	Glass broke due to Rapid Phase Transition.
1974	Barge Massachusetts	Valve leakage after power failure	Loading	No	Deck fracture
1977	Arzew (Algeria)	Wrong valve used	NA	1 death	Valve failure
1977	LNG Aquarius		Loading	No	Tank overfilled
1978	LNG export facility (Das Island UAE)	Failure of a bottom pipe of an LNG tank	NA	No	Spill inside the tank containment
1979	Mostefa Ben-Boulaid Ship	Valve leakage	Unloading	No	Deck fractures
1979	Pollenger ship	Valve leakage	Unloading	No	Tank cover plates fracture
1979	Columbus Gas LNG import terminal (Maryland, US)	LNG leakage from LNG pump	NA	1 death and 1 seriously injured	Explosion

Early 1980s	El Paso Consolidated	Minor release of LNG from a flange	NA	NA	Deck plating fractured due to low temperature embrittlement
1983	Norman Lady (Sodegaura, Japan)	All cargo transfer arms sheared	Prior to unloading	Not reported	LNG spilled without ignition
1985	Isabella	Cargo valve failure	Unloading	No	Cargo overflow, deck fractures
1985	Annabella	Pressurized cargo tank	NA	No	LNG released from the tank or piping
1985	LNG peakshaving facility (Pinson, Alabama US)	Failure of the welds on a “Patch plate”	Unloading	6 injuries	Windows were blown due to escaping natural gas
1989	Tellier	Broke moorings	Loading	No	Hull and deck fractures
1989	LNG peakshaving facility (Thurley, UK)	Inadequate tightening of valve	Unloading	2 injuries	LNG released into the atmosphere resulting in a flash fire
1992	LNG peakshaving facility (Baltimore MD, US)	A relief valve on LNG piping failed to open	NA	No	Spilled LNG caused brittle fracture on the outer shell of the tank

The most catastrophic LNG release accident occurred in Cleveland in 1944 due to failure of a cylindrical tank containing LNG. The spilled LNG evaporated, ignited and exploded, causing 128 casualties, 300 injuries and approximately 7 million dollars of property damage [242]. The Bureau of Mines investigation report [243] showed that the accident was due to the low temperature embrittlement of the inner shell of the cylindrical tank. The inner tank was made of 3.5% (by weight) nickel steel, a material known to be susceptible to brittle fracture at LNG storage temperatures [244]. Currently, instead of this alloy, 9% nickel steel is used as the primary containment barrier [245]. However, other structures are often constructed from steel with much lower strength and toughness than 9% nickel steel. In March, 1977 in Algeria, a worker at the Camel plant was frozen to death when he was sprayed with LNG escaping from a ruptured valve body [240]. The valve ruptured because its body was constructed of low strength material, i.e. cast aluminium. Currently, this part has been changed to stainless steel.

The impact of an LNG spill on structure depends on the phenomenon of pool formation and temperature distribution on the structure. Many factors affect LNG spreading and pool formation on a solid surface such as LNG properties (mixture composition, temperature, pressure); release volume and mode (instantaneous or continuous), location and rate; spreading terrain; the dynamics of vaporization process; atmospheric and wind conditions as shown in Figure 3-1. Due to the intense heat transfer between cryogenic LNG and the surrounding environment, rapid vaporization is a major factor in determining the extent of LNG spreading in the form of a liquid pool. The vaporization occurs as soon as LNG becomes exposed to the atmosphere or comes in contact with any surface. Eventually a steady state is reached which is characterized by the incoming mass equal to the vaporized mass. For a solid surface/ground, the cooling results in a decrease in the heat input, which for a constant spill rate, will lead to a gradually increasing pool size.

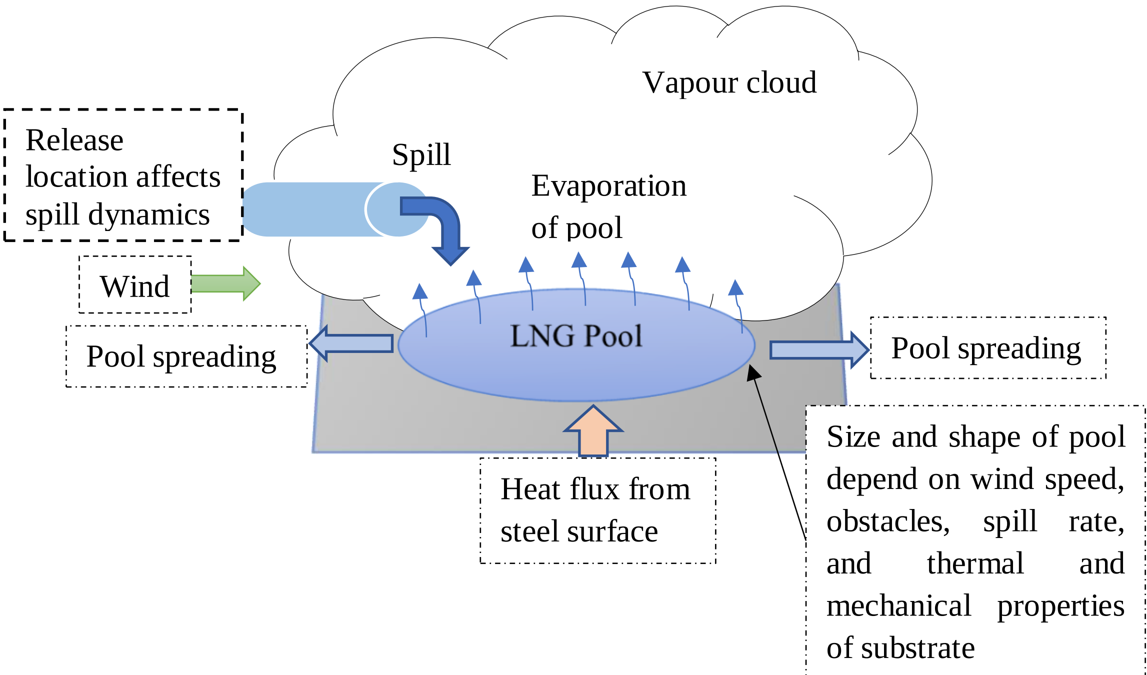

Figure 3-1. LNG pool formation [246]

Any potential damage from an LNG incident would depend on initiating events, volume and location of LNG release, release rate, wind direction and speed etc. The quantitative calculation of probabilities of such event can actually only be done if sufficient data exist. Operational incidents resulting from human error and equipment failures can cause an LNG spill during unloading, loading, storage and production. According to the US Department of Energy, over the 70 years of LNG industry's life, 8 marine incidents have resulted in LNG spillage [247]. The failure of an LNG storage tank subject to contact with cryogenic temperature has been studied by Adamou [46], Fecht *et al.* [47]. The Sandia National Laboratories study [248] revealed that lower fracture toughness bound value was used to estimate potential thermal stress states in ship structural steel for different types of breach and LNG spill events. The study considered three cryogenic spill scenarios for thermal stress calculation each corresponding to a different type of breach event. In all three types of cryogenic spill event, the potential exists for progressive structural damage due to the thermal stress of the cryogenic liquid on structural steel of the ship. To assess how a structural section of an LNG vessel would respond to contact with cryogenic LNG, Petti and Kalan [48] conducted a series of tests in four different phases. This included testing of large steel plates that were constrained on their edges, and the testing of large, three-dimensional steel structures representing LNG vessel structural elements. In Phase I, the testing process was developed and studied the cooling of steel plates subjected to Liquid Nitrogen (LN_2). The plate sizes ranged from 4 ft square plates in Phase II to 12 ft × 3ft structures with more complex geometry in Phase III. A total of 22 structural tests were conducted in Phases II and III, nine of which resulted in cracking. Phase IV investigated differences in heat transfer rates between LNG and LN_2. In order to generate thermally induced fracturing, stress concentrations were introduced with varying degrees of severity. These tests were conducted exposing test samples for a prolonged period of time and focussed on immediate crack growth. Another study [249] was conducted to model and analyse in detail LNG cargo tank breach, LNG spill and flow, to assess cryogenic and fire thermal impacts, and to assess cascading damage potential of an LNG ship and cargo tanks at the Sandia National Laboratories. The study concluded that structural integrity can be severely compromised for large spills with the majority of the inner hull cracked. The aforementioned tests investigated the impact of cryogenic temperature on structure subjected to large scale LNG spill for a prolonged period of time. However, impact assessment of an instantaneous spill of LNG in small to medium quantity has received little attention. This study attempts to fill that gap by proposing a methodology to assess the impact (both immediate and long-term) of leakage of LNG on a steel structure.

3.2. Developed methodology

The present work develops a methodology to assess the impact of an accidental spill of LNG on a steel structure. The proposed methodology is comprised of several steps as demonstrated in Figure 3-2. Each step of this methodology is discussed in detail in the following section.

3.2.1. Identifying a credible leak scenario

Accidental leakage of LNG in a large quantity can be easily detected by detectors, and operators may successfully adopt preventative measures to prevent subsequent consequences or accidents. However, small to medium instantaneous leakage may not be readily detected (10-15 minutes). Often a 2 inch (50.8 mm) leak size is adopted as the maximum permissible leak in the oil and gas industry to determine maximum credible events for Facility Siting Studies (FSSs) [250]. Moreover, leak size selection guidance such as Center for Chemical Process Safety (CCPS) [251] and Dow Chemical Exposure Index [252] also tend to agree in limiting leak to a maximum diameter of 2 inches or a portion of the pipe cross-section as the assumed leak size. Due to lack of consensus regarding selection of allowable hole size, smaller leak sizes are often overlooked, and they are not paid due attention in risk analysis [253]. This does not mean that smaller leaks are safe or do not pose any hazard. In congested and confined areas such as a Floating LNG facility, smaller leaks of LNG pose serious hazards such as fire, Vapour Cloud Explosion (VCE) and brittle fractures. In a large complex processing facility, there can be numerous fugitive leak scenarios and it is not feasible to consider all scenarios in risk assessment. As a remedy to this limitation, credible accident scenario assessment methodology can be used, and more credible scenarios can be used for safety analysis [34]. Pitblado et al. [254] have identified several maximum credible events based on credible holes such as 250 mm is considered as the maximum credible puncture hole and 750 mm is the maximum credible hole from accidental operation events. Woodward and Pitblado [15] stated that smaller leak sizes of 10-25 mm are highly likely in an LNG plant lifetime. There is no universal consensus on a credible leak size which is obvious due to diverse operating conditions and dependence on specific cases. In order to select credible release sizes and scenarios several approaches are used such as worst case scenario [255], maximum credible accident scenario methodology [256, 257] and quantitative risk assessment approaches and experts [258].

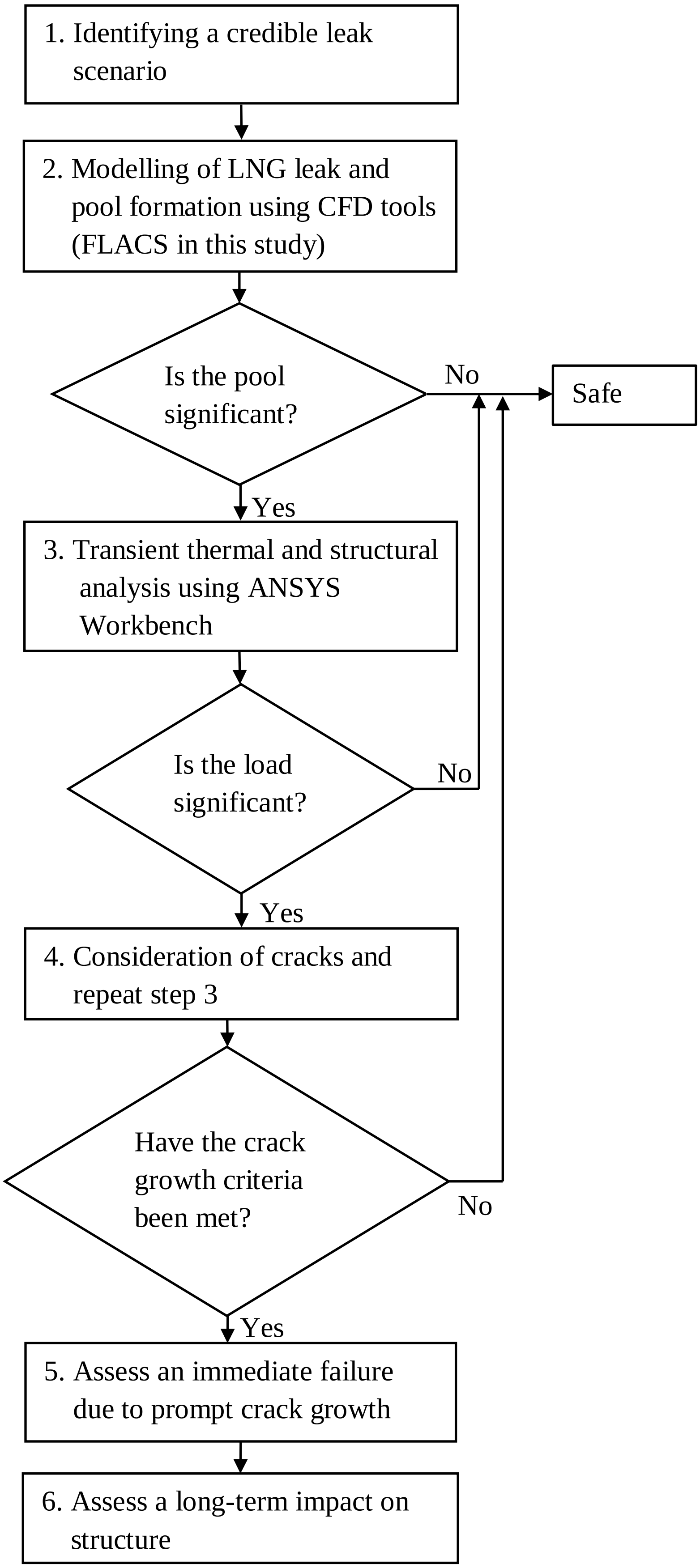

Figure 3-2. Proposed methodology for assessing crack growth and fatigue failure after accidental release of LNG on steel structure in congested marine offshore facility.

3.2.2. Modelling of LNG leak and pool formation using CFD tool (FLACS)

The credible leak scenarios identified in the previous section are considered for CFD simulation. Among available CFD models, FLACS, developed by the Global Explosion Consultants (GexCon AS), is widely applied for the modelling of gas dispersion and explosion after accidental release in congested onshore or offshore facilities [259]. FLACS has been improved and validated by many studies to confirm its predictions as reasonable and acceptable [260]. Due to this, FLACS is used in the present study. For an appropriate pool formation modelling using CFD code, a reliable representation of boundary conditions, initial conditions and atmospheric parameters is important. A detailed guideline for modelling leak and pool formation is found in FLACS user manual [261]. The post-processing results of this simulation are used to assess the impact of cryogenic temperature on the structure.

3.2.3. Transient thermal and structural analysis

During an accidental release of LNG, modelling the crack initiation and propagation on spilled surface due to cryogenic temperature is important for structural integrity and safety. The surface temperature profile of the spilled surface, obtained from the FLACS simulation, is transferred to ANSYS workbench 18.1 [262] and transient thermal analysis is performed in order to replicate the temperature distribution on the plate. Furthermore, considering surface temperature profile as the load, the behaviour of the structure is modelled using static structural analysis. The thermal load is applied to the geometry having fixed support on the edges. Loading conditions similar to those expected in real conditions are applied to the uncracked geometry, and the region with the highest stress concentration is identified.

3.2.4. Consideration of crack

After identifying the high stress concentration location, a flaw/crack is inserted in the geometry such that it is perpendicular to the maximum principal stress direction at that location. Most cracks and planar flaws can be classified into five general categories: i) surface-breaking flaws, ii) through flaws, iii) subsurface/embedded flaws, iv) corner flaws, and v) and edge flaws [263]. Surface cracks are among the more common flaws in aircraft and pressure vessel components. A common semi-elliptical crack is controlled by two parameters, namely; crack length and aspect ratio [264]. Crack growth depends on initial crack size. For actual initial crack size larger than 0.02 inches (0.508 mm), long crack growth models such as the Paris, Walker or Forman models can be used directly [264]. Some studies used empirical crack lengths between 0.25 mm and 1 mm for metals [265, 266]. After inserting any acceptable flaw/crack sizes in the high stress concentration area, the transient and static structural analysis is repeated to assess the impact of thermal stress on the crack. The impact is mainly categorised into an immediate failure (immediate crack propagation) and long-term impact due to thermal contraction.

3.2.5. Assess an immediate failure due to prompt crack growth

The phenomenon of stable crack growth in materials is studied using efficient techniques to simulate crack propagation and fracture criteria [267]. The stress intensity factor (SIF) (K), the elastic energy release rate (G), the J-integral, the crack-tip opening displacement (CTOD), and the crack-tip opening angle (CTOA) are the most important criteria used in fracture mechanics [268]. Irwin [269] proposed K factor (SIF) to describe the intensity of elastic crack-tip fields, where the K factor denotes the linear elastic fracture mechanics. The J-integral was proposed by Rice [270] in 1968 to characterize the intensity of elastic–plastic crack-tip fields, and symbolizes the elastic–plastic fracture mechanics. In 1963 Wells [271], proposed the CTOD concept based on practical application of K or J. Some widely used fracture criteria proposed by different authors are given in Table 3-2. Fracture criteria are basically a balance of the crack tip loads and the material's fracture resistance or toughness. Different experimental methods are available for measuring these parameters to describe fracture toughness of materials [272, 273].

Crack front characterisation plays a dominant part in the initial growth of the crack. The state of the end region is described by the value of the J-integral. When J reaches a critical value (J_C), the crack starts to grow. J is determined by FE method without detailed knowledge of the situation near the crack tip. Since the J integral is a field parameter, J_{IC} fracture criteria is compatible with any criteria based on features specific to the crack tip region. Precise computation of the field in the crack tip region is not necessary [274].

Table 3-2. Commonly used fracture criteria

Literatures	Comments	Criterion Fracture occurs when
Inglis [275]	Involves crack tip radius and crack length	Crack tip stress becomes equal or greater than fracture stress ($\sigma \geq \sigma_f$)
Griffith [276]	Involves crack length	Crack tip stress becomes equal or greater than fracture stress ($\sigma \geq \sigma_f$)
Irwin [269]	Concept of stress intensity factor or energy release rate	SIF (in mode I) becomes equal or greater than critical SIF ($K_I \geq K_{IC}$), or Energy release rate becomes equal or greater than critical energy release rate ($G \geq G_C$)
Wells [271]	Involves crack (tip) opening displacement	Crack tip opening displacement becomes equal or greater than critical opening displacement ($\delta \geq \delta_C$)
Rice [270]	Applicable to non-linear elastic and elastic-plastic materials.	J-Integral value becomes equal or greater than critical J-integral ($J \geq J_C$)

Crack front characterisation plays a dominant part in the initial growth of the crack. The state of the end region is described by the value of the J-integral. When J reaches a critical value (J_C), the crack starts to grow. J is determined by FE method without detailed knowledge of the situation near the crack tip. Since the J integral is a field parameter, J_{IC} fracture criteria is compatible with any criteria based on features specific to the crack tip region. Precise computation of the field in the crack tip region is not necessary [274].

The SIF method is used for linear isotropic elasticity in which Stress Intensity Factor (SIF) is calculated at different crack lengths. The SIF describes the stress state at a crack tip, which is related to the rate of crack growth. It is used to establish failure criteria due to fracture. According to the Irwin criterion, the crack will grow if stress intensity factor ($N/m^{3/2}$) becomes equal or greater than the critical stress intensity factor or fracture toughness ($N/m^{3/2}$) of material. The critical intensity factor is independent of the crack geometry and loading and is regarded as a material property. SIF depends on loading mode, crack shape and component, specimen, or structure configuration. According to Stephens *et al.* [182] values of K for various loadings and configurations can be calculated using:

1. The theory of elasticity involving (i) analytical calculations and (ii) computational calculations (i.e. Finite Element Analysis (FEA)), and

2. Experimental methods (i.e. photo-elasticity)

Fatigue failure generally consists of three stages: (I) initiation of a crack, (II) propagation of cracks and (III) final failure [277]. Stage I consists of the development of microstructural damage such as micro cracks or slip bands which will grow and eventually coalesce to form a dominant crack. In this region, the crack starts to grow at a given threshold value, that is the minimum value of the stress intensity factor where the crack start to propagate. The final region of the crack growth rate curve is related to the fracture toughness of the material, where a small increase in the stress intensity amplitude produces a large increase in crack growth rate. In stage II, the dominant crack grows stably and linearly under the application of repeated loads with an increase in stress intensity and crack growth. In this region, crack growth rate has a linear relation with the stress intensity factor and is commonly modelled by the Paris law [278]. In stage III, the crack grows unstably such that SIF (K) reaches the fracture toughness value (K_{IC}) or $K > K_{IC}$ and the component can fail unstably. A comprehensive study of all three stages is necessary for fatigue analysis of a component.

During cyclic loading condition, cyclic fatigue failure occurs if SIF value becomes greater than the threshold value (K_{th}). To assess the crack growth, the maximum SIF value (mode I) can be compared against K_{th}. Similarly, the SIF is compared against the fracture toughness of the material for immediate fracture failure analysis. An immediate fracture occurs when SIF value becomes equal to, or greater than K_{IC}. The threshold value and fracture toughness depend on material property and loading condition [277]. When the immediate crack propagation criterion is not met, then fatigue failure life of the structure needs to be assessed in order to identify a potential long-term impact.

3.2.6. Assess a long-term impact on structure

Low temperatures can adversely affect the tensile toughness of many commonly-used engineering materials. Due to this, it is important to investigate a long-term impact of an LNG spill on a structure that is once exposed to cryogenic temperatures of LNG. Time-dependent crack propagation in the presence of cyclic stresses is a major concern in all structural systems [277]. When a component is subjected to cyclic loading, failure of the component depends on the number of cyclic stresses and the amount of load, in addition to crack size and other damage mechanisms. Various deterministic models have been developed to predict fatigue crack growth in metallic materials, giving much emphasis to approaches suitable for variable amplitude load histories. Machniewicz [279] reviewed and classified the various deterministic models available for fatigue growth prediction as illustrated in Figure 3-3.

In the present study, FE model is chosen to assess a potential long-term impact on the design life of a structure that is once accidentally exposed to LNG. FE model has been widely used for fatigue crack growth simulation and failure prediction in various studies [280-282].

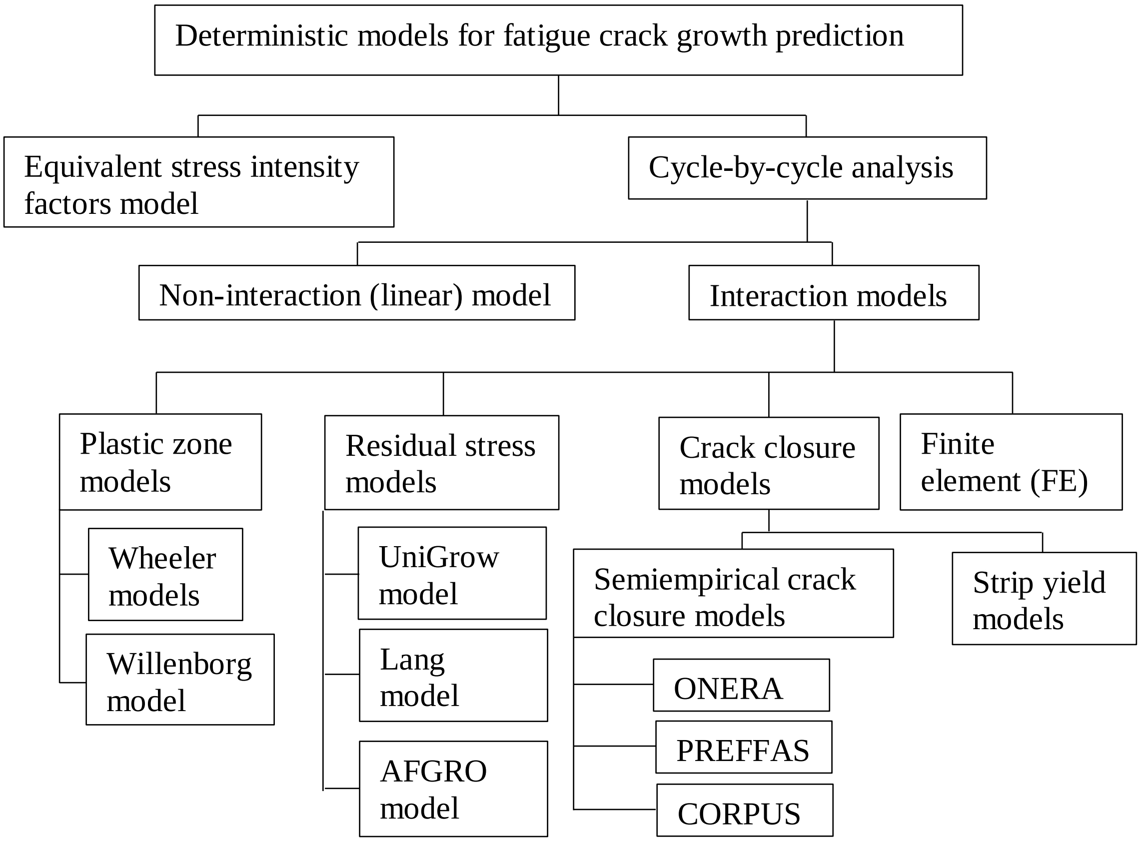

Figure 3-3. Classification of deterministic models for fatigue crack growth predictions

The damage life of the steel plate is obtained using the Workbench fatigue tool with parameters shown in Table 3-3. The design life is taken as 10^9 cycles. The behaviour of the fatigue is analysed considering a constant amplitude, proportional loading. The fatigue strength factor (K_f) is assumed as 0.95 to account for the existence of initial flaw or crack in the structure.

Table 3-3. Details of fatigue tool

K_f	0.95
Load type	Fully reversed
Load factor	1
Design life	10^9 cycles
Analysis type	Stress life
Mean stress theory	Goodman
Stress component	Equivalent (Von-mises)
Life unit name	cycles
1 cycle is equal to	1 cycle

3.3. Application of the methodology (A case study)

The proposed methodology is applied to the liquefaction module of a floating LNG processing facility as shown in Figure 3-4. Due to unavailability of adequate data about fugitive LNG leaks, frequency and consequence, a credibility assessment of several leakage scenarios is difficult to perform. In this study, LNG leakage from a puncture hole of 25 mm from a process line is considered as the maximum credible leak size. This is because of the high likelihood of occurrence and permissible leak size. In the past, fatal accidents have occurred in the liquefaction module. For instance, in 2004, 27 people were killed from an explosion in a steam boiler in Skikda, Algeria [283]. In addition, most operating conditions in the liquefaction process have high temperature and pressure resulting in higher risk of fire and explosion [33]. Because of this, leak location is chosen in Mixed Refrigerant (MR) module of the liquefaction process as shown in Figure 3-4.

The leak and pool formation is modelled considering 10 m × 10 m × 0.01905 m dimensions. These dimensions are considered according to past LNG spill tests [48]. An appropriate representation of boundary condition is required for high accuracy of CFD simulation results [284]. According to Luketa-Hanlin et al. [285], seven boundary conditions are required for an LNG simulation: inlet, outlet, top, two sides, bottom, and LNG pool.

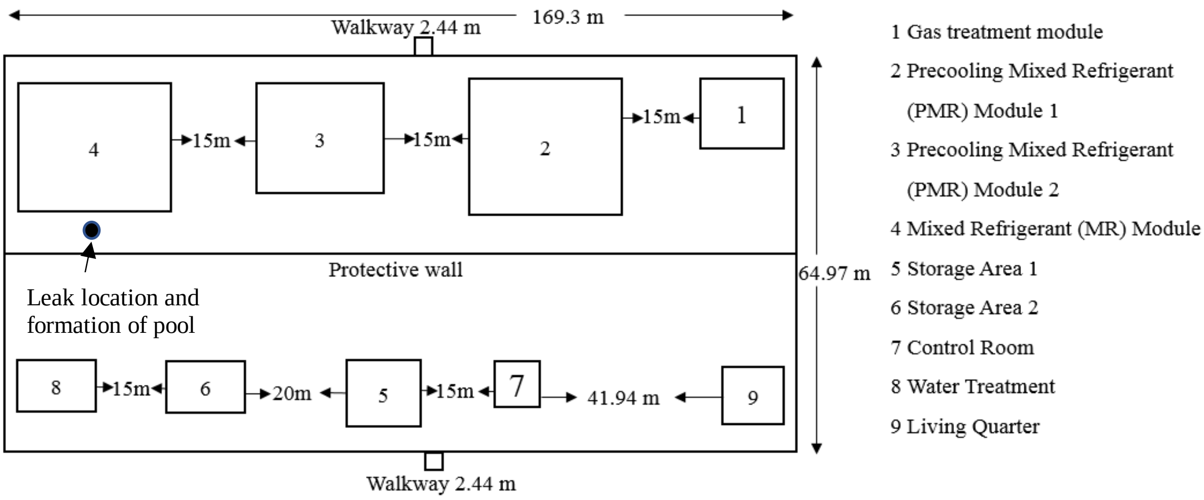

Figure 3-4. Layout design of an FLNG facility [286].

The outlet boundary is considered to be open assuming that the flow is fully developed, unidirectional and variables are constant in the flow direction. All boundaries are kept sufficiently far from the potential LNG leak location to avoid their effects on pool formation and spreading phenomena. The top boundary is also considered as an open external flow boundary. The side boundaries are kept open and are placed sufficiently distant to maintain an appropriate flow symmetry. Wind flows from lower y-axis with velocity of 3 m/s along +Y direction considering 10 s wind build-up time. Other boundaries are kept as a nozzle. The initial conditions considered in this simulation are given in Table 3-4. Characteristic velocity is used to find values for initial turbulence fields and it should take a positive or a zero value [261]. The characteristic velocity (3 m/s) is considered according to FLACS's recommendation for best practice [261].

Table 3-4. Initial conditions considered in the simulation

Parameters	**Value**
Characteristic velocity	3 m/s
Relative turbulence intensity	0.01
Turbulence length scale	0.1
Temperature	20 °C
Ambient pressure	100 kPa
Ground height	0 m
Surface roughness	0.001 (logarithmic wind profile)
Pasquill atmospheric stability class	D (Neutral)

Typical LNG vapour consists of 95% methane, 4% ethane and 1% propane [261]. Release scenario depends on various parameters such as leakage velocity, leaked size and pressure at the leakage. The characteristics of LNG pool formation depend on the types of surface. Pool formation and spread on water surface is different from that on land. To define a time varying spill profile for the pool model, a constant release rate of 2 kg/s is assigned through a 0.0005 m^2 leak hole (through a hole diameter of 2 inches). It is considered that LNG is instantaneously spilled on a flat surface in the presence of obstacles. The LNG leaks at a constant release rate (of 2 kg/s) for 20 s and then the release rate linearly decreases during simulation. The total simulation time is considered as 100 s. The values of pool parameters considered in the simulation are given in Table 3-5. A dynamic pool model (PM3) is considered which means that the pool spreads with non-uniform pool temperature due to the influence of heat and mass transfer in each control volume [261].

Table 3-5. Parameters used in the pool simulation

Pool model	Dynamic (PM3)
Start time	0 s
Mass rate inserted uniformly over the initial pool area	2 kg/s
Outer radius	0.5 m
Ground temperature	293.15 K
Heat from the sun	400 W/m^2
Ground roughness	0.001
Ground type	Plate
Plate thickness	0.0191 m (0.75 in)
Specific heat of LNG pool material	2.226×10^3 J/(kgK)
Ground thermal diffusivity	3.9×10^{-6} m^2/s
Evaporation heat of LNG	5.1×10^5 J/kg
Kinematic viscosity for air	1.568×10^{-5} m^2/s
Molecular weight of the LNG	16
Temperature of the pool	111.15 K

The shape of the pool obtained using the FLACS simulation is presented in Figure 3-5. The distribution of temperature after the release of LNG on the surface is illustrated in Figure 3-5. The temperature distribution and the pool shape are observed at the simulation time of 70 s. The maximum and the minimum temperatures noted at 70 s are 291.1 K and 0 K respectively.

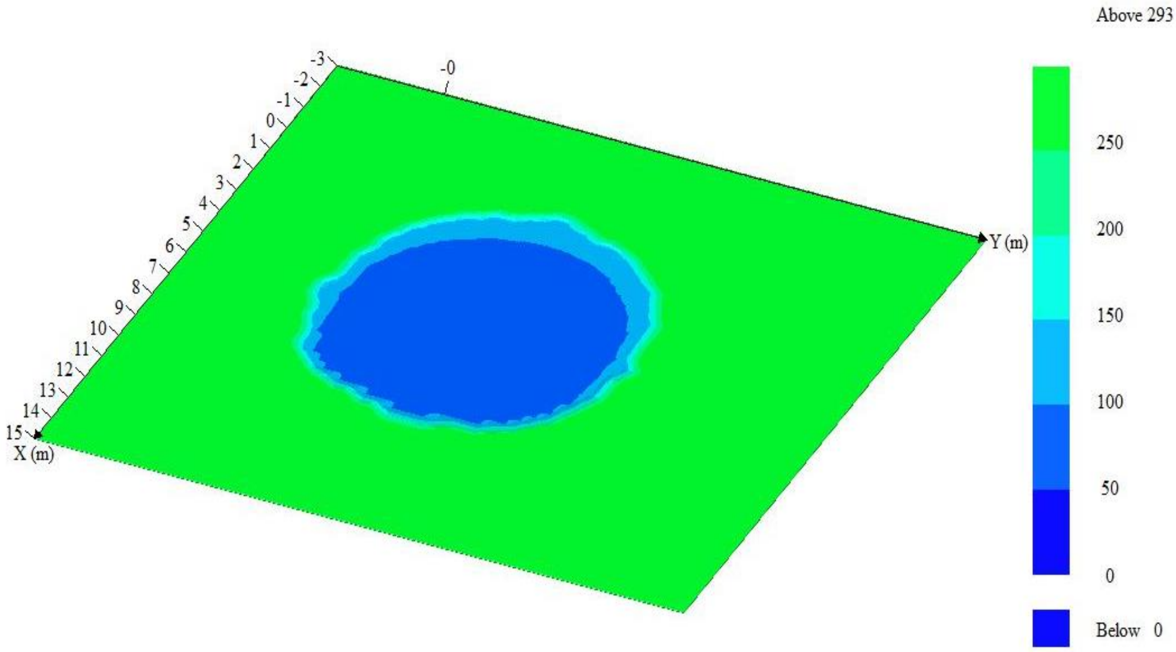

Figure 3-5. Pool formation and its temperature at 70 s

The thermal load is applied to the structure, assigning fixed support on all edges. According to the Sandia National Laboratories study [248], ABS Class A, B, and C are extensively used in LNG ship fabrication. For these steels, the fracture toughness (K_C) decreases approximately linearly from 90 kpsi$\sqrt{in}$ at 222.04 K (-51.11 °C) to 20 kpsi$\sqrt{in}$ (21.97 MPa$\sqrt{m}$) at 110.928 K (-162.2 °C). The structure is assumed to be made of ABS Class B steel. Loading conditions similar to those expected under real conditions are applied and the region with a high stress concentration is identified by performing the static structural analysis.

In this current study, semi-elliptical surface cracks are considered because most surface flaws are represented as semi-elliptical [287, 288]. Semi-elliptical crack is one of the most common flaw types to be found in any structures [289, 290] such as pipes, internally pressurised vessels and structures under stress [291, 292]. In a semi-elliptical crack, ends of a crack get more damage than the deepest part of the crack and this defines the corresponding crack growth life of the whole crack [293]. A common semi-elliptical crack is controlled by two parameters, namely; crack length and aspect ratio [264]. As the length of a semi-elliptical crack is more dominant than its width for crack propagation, this current study considered different crack lengths for assessing an immediate crack propagation. Surface crack sizes; 30 mm, 25 mm, 20 mm, 10 mm, 8 mm, 6 mm, 2 mm, 1 mm and 0.8 mm are considered in the identified high stress concentration region to account for wider possibilities. In the small spill event scenario considered by the Sandia report [248], the critical flaw size (crack-like defect) was found to be about 0.1 inches (0.254 mm) which would be relatively common in ship fabrication. The location of a semi-elliptical crack is illustrated in Figure 3-6. After considering the crack parameters, the static structural analysis of the structure is performed again employing the thermal load and fixed support. The impact of cryogenic temperature on steel structure is assessed according to immediate failure and or cyclic loading fatigue failure.

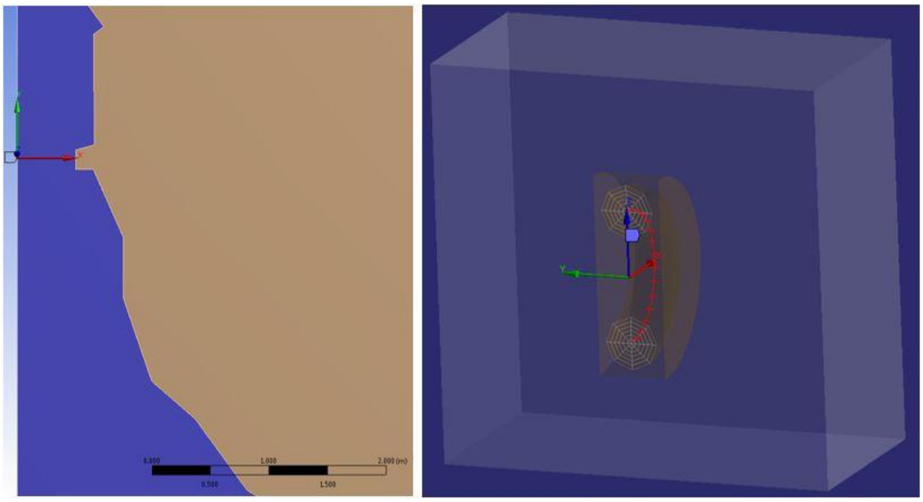

Figure 3-6. Location of a semi-elliptical shape crack

3.4. Results and discussion

The significance of the proposed methodology is explained considering the results of the case study. The unavailability of fugitive LNG leak dataset due to inadequate operating LNG facilities created difficulty in the credibility assessment of fugitive leak scenarios. When LNG leak dataset becomes available, assessment of credibility of occurrence of leakage scenarios will be feasible. Based on past studies and expert judgment, LNG leak from a 25 mm rupture hole was assumed as the most credible leak size in the current case study.

After identifying a credible leak size and location, LNG spill and pool formation were modelled using FLACS. The shape of the pool appeared circular as seen in Figure 3-5. The pool parameters such as mass, temperature, pool area and evaporation rates are illustrated in Figure 3-7 (a, b, c and d). The pool mass increased up to 32 s with the maximum mass of 43.84 kg (shown in Figure 3-7 (a)). The temperature variation of the pool is shown in Figure 3-7 (b) and the lowest temperature is recorded as -263.15 °C (10 K). The time dependent pool area is demonstrated in Figure 3-7 (c) which shows that the maximum area is 45.9 m^2 at 42 s and zero at 95.40 s. The maximum evaporation rate occurred at 0.86 kg/s at 50 s and zero at 95 s as illustrated in Figure 3-7 (d).

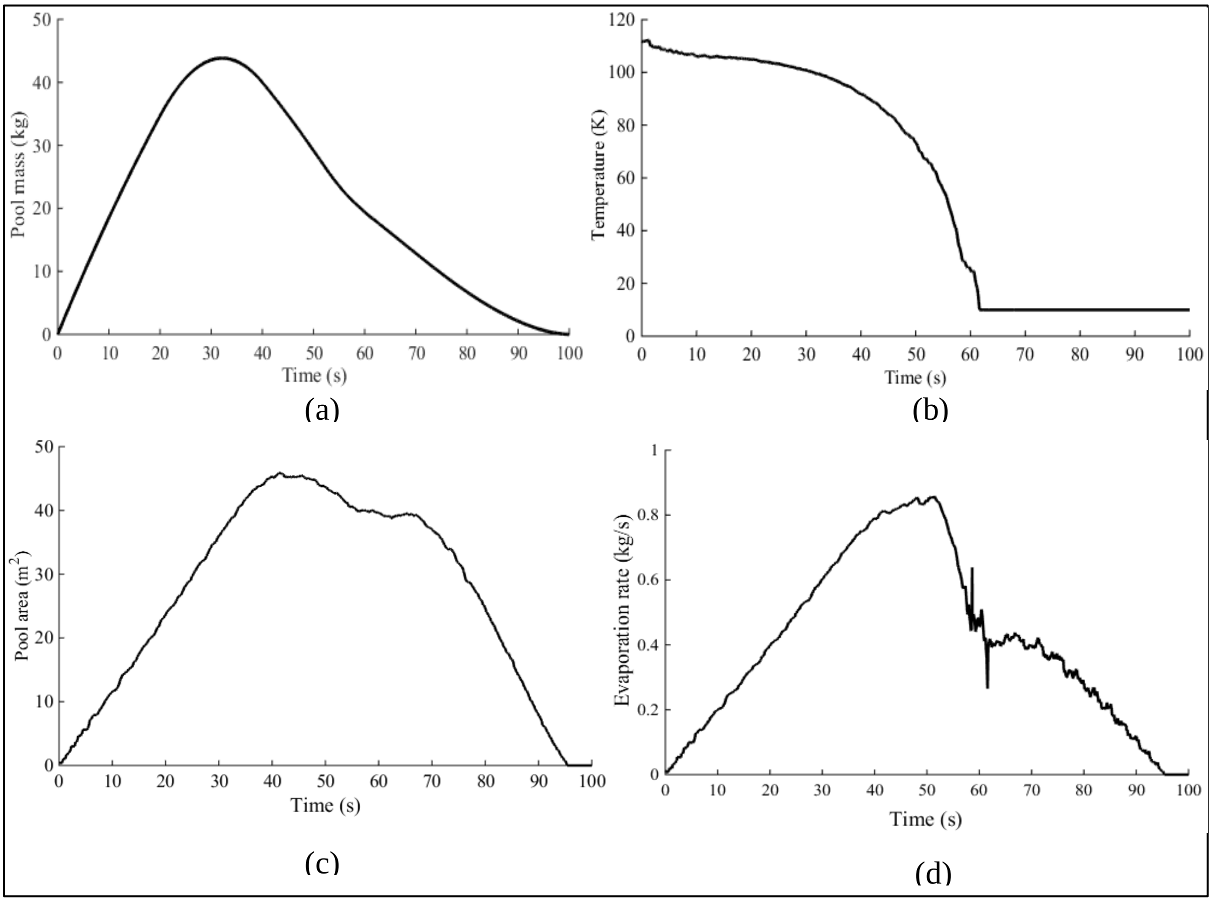

Figure 3-7. Trend of pool (a) Pool mass (kg), (b) Temperature (K), (c) Pool area (m^2) and (d) Evaporation rate (kg/s).

The regions with maximum (Von-Mises stress) stress obtained from the static structural analysis are illustrated in Figure 3-8. The maximum stress is 136.50 MPa. The regions with maximum stress are considered to be the location for potential crack initiation.

For the occurrence of immediate crack propagation and failure, the SIF value must be equal or greater than the fracture toughness of the material. The maximum SIF values (K1, K2 and K3) corresponding to different crack sizes are given in Table 3-6. The maximum K1 value is higher than K2 and K3. This suggests that the crack growth may occur due to tensile loading condition and tearing and shearing loads (K2 and K3) can be ignored.

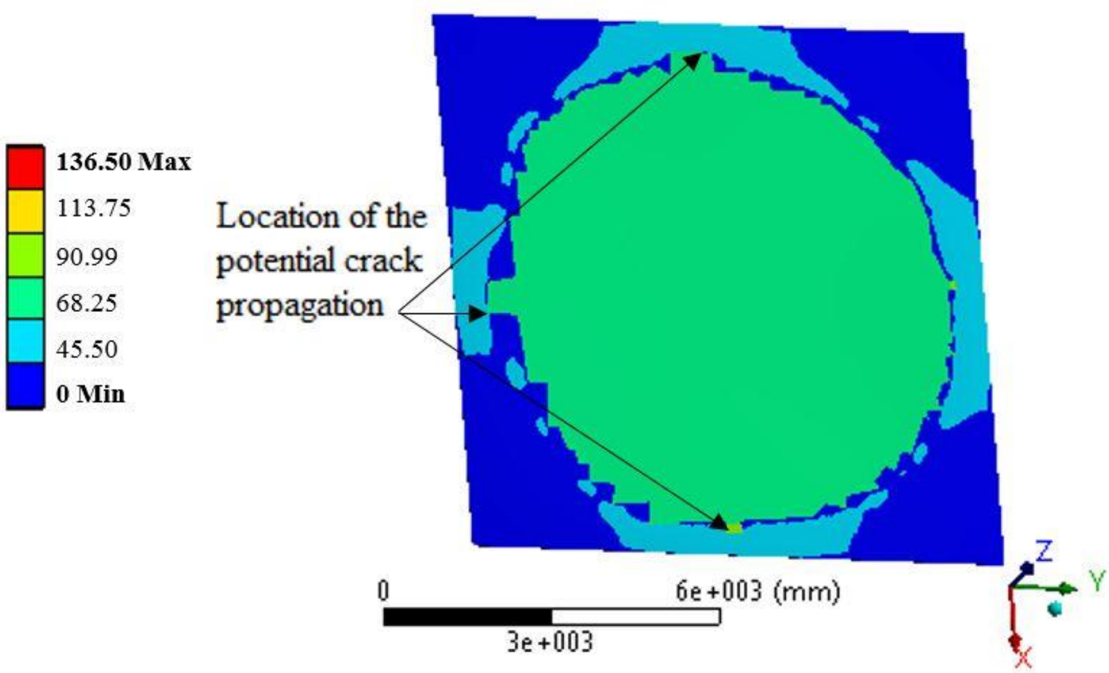

Figure 3-8. Location of the potential crack and its propagation in high equivalent stress

The maximum K1 values corresponding to different crack lengths are plotted as shown in Figure 3-9. This shows that under a constant loading condition, SIF value increases with crack size in immediate non-propagating cracks. This is consistent with past studies and experimental results [294]. The SIF value along a crack trajectory often varies. For instance, the variation of K1 value at different positions along the crack trajectory in the case of a 2 mm crack length is illustrated in Figure 3-10. This shows that SIF (K1) is maximum at the centre of crack front and minimum near the crack tip, i.e. at the start and the end of the crack front. The maximum and the minimum SIF (K1) values are 5.989 MPa $\sqrt{m}$ and 0.443 MPa $\sqrt{m}$ respectively. As the maximum SIF (K1) is lower than that of the fracture toughness of the material, the crack may not propagate immediately. However, this indicates that the crack may start to propagate from the front when loading condition (stress) is met.

Table 3-6. Maximum SIF values corresponding to different crack lengths

Crack lengths (mm)	**SIF (K1) (MPa$\sqrt{m}$)**	**SIF (K2) (MPa$\sqrt{m}$)**	**SIF (K3) (MPa$\sqrt{m}$)**
30	12.659	0.945	0.845
25	12.559	1.732	1.978
20	12.547	0.040	1.923
10	10.336	0.807	0.656
8	10.089	0.069	0.063
6	8.601	0.684	9.470
4	7.686	0.737	9.351
2	5.989	0.396	0.364
1	4.122	0.338	0.267
0.8	1.412	0.090	0.667

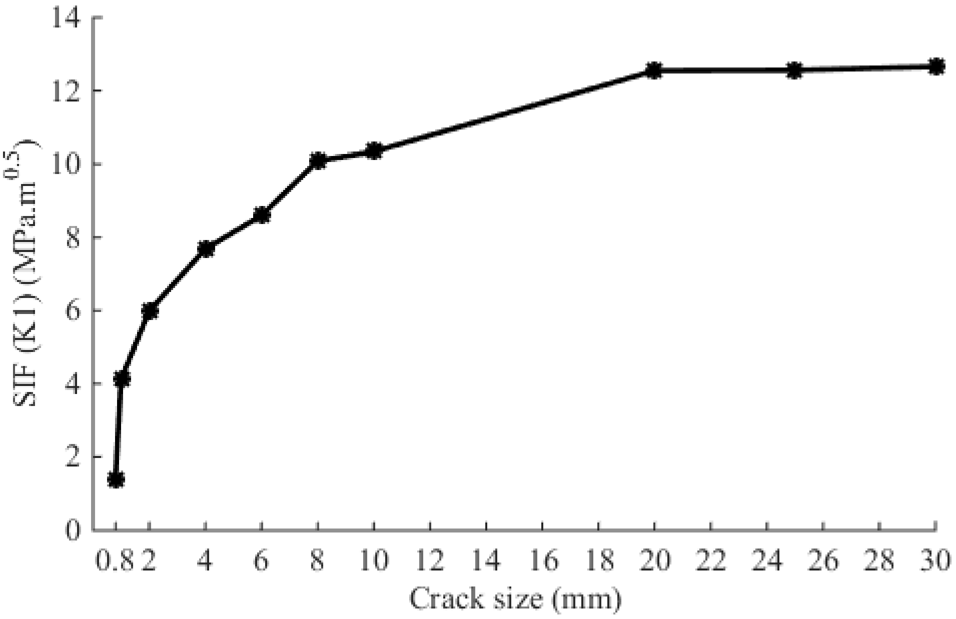

Figure 3-9. K1 values corresponding to different crack sizes

Figure 3-10. The variation of SIF value (K1) along the crack trajectory in a 2 mm crack length

The SIF values obtained from FEA static structural analysis in different crack lengths are compared against the fracture toughness (K_C) of the ABS Class B steel. According to the ASM International [295], the plane stress K_C of ABS Class B steel is 21.97 MPa $\sqrt{m}$. An immediate failure did not occur in any considered crack size because the SIF values were much lower than the fracture toughness of the steel. This shows that the thermal contraction caused by fugitive LNG spills on the steel did not cause an immediate impact to the steel structure. However, during cyclic loading condition, fatigue crack growth initiation (propagation) occurred gradually when the SIF value became equal or greater than the threshold value (K_{th}).

For estimating the life of the steel structure that has been exposed to cryogenic temperature of LNG, fatigue results such as life, damage and safety factor obtained from fatigue analysis were used. In the case of constant amplitude loading, life represents the number of cycles until the component will fail due to fatigue. To demonstrate the fatigue life of the structure that was exposed to cryogenic temperature (thermal stress), a crack with 2 mm length was considered as a case study. The minimum and the maximum cycles are derived from the fatigue analysis of the structure containing the 2 mm crack. The maximum and the minimum cycles denote the service life of the structure when it is exposed to the stress. The minimum and maximum life of the structure were found to be 131.39 and 10^6 cycles respectively. This indicates that with the current constant amplitude loading, the expected model life would be 131 cycles with a maximum life up to 10^6 cycles. Similarly, the fatigue damage of the component is estimated by dividing the design life by the available life. A fatigue damage greater than 1 indicates that the component will fail from fatigue before the design life is reached [296]. This shows that the thermal stress can cause adverse impact on design life of a component.

3.5. Conclusions

An accidental spill of LNG on a steel surface would cause embrittlement or brittle fracture due to the cryogenic temperature. A methodology is proposed and applied to the layout of a typical FLNG processing facility considering a fugitive leak scenario of LNG. Ten semi-elliptical crack sizes are considered in a 10 m × 10 m × 0.01905 m plate. In all considered cracks, stress intensity factors were found to be smaller than the fracture toughness of the steel which suggests that an immediate crack propagation would not occur. To assess a potential long-term impact on the design life of the structure that is once accidentally exposed to LNG, a fatigue damage analysis was conducted. The analysis result demonstrates that the minimum and the maximum life of the steel were found to be 131 and 10^6 cycles respectively, which reveals that the steel plate will fail before reaching the design life. This indicates that the thermal stress resulting from a fugitive LNG spill reduces the maximum design life of a material and would pose a serious hazard to the structural integrity of the facility. The current study can be extended to analyse impact on the microstructure of materials due to cryogenic temperature. This work can be further improved using probabilistic methods of spill and crack growth. The uncertainty associated with material characterisation or property could also be modelled using probabilistic approaches. This would improve reliability of thermally induced failure of an asset caused by an LNG spill.

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Chapter 4

Accidental Release of Liquefied Natural Gas in a Processing Facility: Effect of Equipment Congestion Level on Dispersion Behaviour of the Flammable Vapour

Abstract

An accidental leakage of Liquefied Natural Gas (LNG) can occur during processes of production, storage and transportation. LNG has a complex dispersion characteristic after release into the atmosphere. This complex behaviour demands a detailed description of the scientific phenomena involved in the dispersion of the released LNG. Moreover, a fugitive LNG leakage may remain undetected in complex geometry usually in semi-confined or confined areas and is prone to fire and explosion events. To identify location of potential fire and/or explosion events, resulting from accidental leakage and dispersion of LNG, a dispersion modelling of leakage is essential. This study proposes a methodology comprising of release scenarios, credible leak size, simulation, comparison of congestion level and mass of flammable vapour for modelling the dispersion of a small leakage of LNG and its vapour in a typical layout using Computational Fluid Dynamics (CFD) approach. The methodology is applied to a case study considering a small leakage of LNG in three levels of equipment congestion. The potential fire and/or explosion hazard of small leaks is assessed considering both time dependent concentration analysis and area-based model. Mass of flammable vapour is estimated in each case and effect of equipment congestion on source terms and dispersion characteristics are analysed. The result demonstrates that the small leak of LNG can create hazardous scenarios for a fire and/or explosion event. It is also revealed that higher degree of equipment congestion increases the retention time of vapour and intensifies the formation of pockets of isolated vapour cloud. This study would help in designing appropriate leak and dispersion detection systems, effective monitoring procedures and risk assessment.

Keywords: Complex layout, LNG, fugitive leakage, dispersion modelling, CFD, FLACS

4.1. Introduction

High demand for the consumption of natural gas, (LNG), means an outstanding increase in production, storage and transportation of natural gas [234]. Hence, the potential hazards of LNG spills and the associated impacts on the exposed population and environment is of major concern [247]. To assess potential risk of LNG spills and the consequences, it is vital to study LNG vapour dispersion behaviour. After the leakage, LNG hazards can be evaluated in three stages: source term (pool development and its evaporation); dispersion; and effects (due to fire thermal radiation and/or explosion overpressure) [297]. To identify and assess the risks of LNG release, hazards of each phase need to be considered. Being 1.5 times heavier than air, after release into the atmosphere, the dispersion of LNG occurs in three phases: negative buoyancy dominated; stably stratified; and passive dispersion [298]. The dispersion of LNG mainly depends on the evaporation rate of LNG pool and atmospheric effect. The LNG vapour initially released from spill is denser than the air and forms a vapour cloud around the release location close to the ground. The buoyancy is not dominant at this stage and the vapour disperses into the surrounds due to the wind. The atmospheric condition also matters at this phase by warming the vapour due to conduction when it is diluted in the surrounding environment [15]. This causes instantaneous vaporisation of LNG due to its cryogenic nature which leads to the formation of a flammable vapour cloud [299]. Considering its complex dispersion behaviour, a detailed understanding of spilled LNG behaviour is required for the accurate prediction of potential consequences.

An accidental LNG release and its dispersion may cause severe consequences such as structural failure due to brittle fracture, asphyxiation, and fire and explosion. Dispersion of combustion products released after LNG vapour fire and explosion also presents a serious hazard to humans and the surrounding structures [23]. These events may lead to fatalities and financial losses. Past LNG accidents are reported in Woodward and Pitblado [15]. For example, fire and explosion occurred in a LNG facility in Skikda, Algeria on 19 January 2004 which resulted in 27 casualties, 56 injuries and $900 million loss [300]. Either LNG or refrigerant leakage from a defective pipe used to transport LNG and hydrocarbon products in liquid state was identified as a primary cause of the fire and explosion event [300]. The release rate was about 10 kg/s [301]. More recently, on 3 March 2014, the Plymouth-Liquefied Natural Gas Peak Shaving Plant experienced a catastrophic failure which resulted in an explosion in a portion of the facility’s LNG-1 purification and regeneration system [302]. The investigation report [302] found that the primary cause of this accident was operator error which led to vessel and piping failure from detonation caused by internal auto-ignition due to a purge that failed to remove a gas air mixture from the system. The incident injured 5 employees and cost $45,749,300. This shows that formation of a flammable vapour cloud after the release of LNG is a major issue. The wide flammability range of natural gas makes its dispersion behaviour a critical priority to be fully understood. If an ignition source is present and the vapour air mixture is in its flammable range, the vapour cloud will ignite and catastrophic consequences are likely [303]. The US Federal Regulation 49 CFR Part 193.2059 [304] and standard NFPA 59A [305] require the use of validated consequence models to predict potential hazardous areas adjacent to LNG facilities in the event of an accidental LNG spill [306]. For quantitative risk assessment of an accidental LNG spill, no sufficient data are available to calculate LNG leak frequency in LNG production and receiving facilities. To avoid this limitation, Kim et al. [307] provided the top events of major LNG releases from membrane type LNG storage tanks and associated pipes considering release scenarios of overfilling, over-pressurisation, under-pressurisation, failure of inlet lines and outlet lines and loss of mechanical integrity of the tank using Fault Tree analysis. Based on these failure mechanisms, total leak frequency was found to be 5.2×10^{-5} per year. However, this may not be adequate for risk assessment and management of a large and complex facility with liquefaction and offloading processes.

Some large scale experiments and tests were carried out to gain an understanding of spill and dispersion characteristics of LNG such as the Burro series [21], Coyote series [36], Falcon series [20], Maplin Sands tests [37], Esso tests [38], Shell jettison tests [39], Avocet [40], and Brayton Fire Training Field (BFTF) [41]. Due to the difficulties, costs, and risks involved in conducting such experiments, computational modelling of LNG spill and dispersion is strongly favoured [308]. To model LNG vapour dispersion, there are various approaches with different levels of complexity are available, i.e. simple empirical models, integral, shallow-layer models and fully three-dimensional CFD models [309]. The use of CFD codes for LNG vapour cloud dispersion simulation is strongly recommended by the Sandia National Laboratories 2004 report [248]. CFD modelling allows for the representation of complex geometry and its effects on flow and dispersion [41, 310]. According to Cormier *et al.* [41] four publicly available CFD codes are widely used for LNG dispersion modelling namely FEM3 [311], Flame Acceleration Simulator (FLACS) [260], ANSYS Fluent [310] and ANSYS CFX [306, 312]. Moreover, Open Field Operation and Manipulation (OpenFoam) [313] and Fire Dynamics Simulator (FDS) have also been used for LNG dispersion modelling [314].

Past LNG dispersion modellings were studied based on spill into impoundment [310, 315], over water [248, 316, 317], trenches [314, 318] and terrain [319]. These studies were performed incorporating large leaks of gas or LNG vapour. The large-scale field tests for LNG dispersion are summarised in Table 4-1.

Table 4-1. Large scale LNG dispersion tests

Name	Trial number	Atmospheric condition based on Pasquill Stability Classes	Wind speed (m/s)	Dispersion over land (L) or water (W)	Mass flow rate (kg/s)	Release duration (s)
Maplin Sands 1980 [320]	27 34 35	C-D D D	5.5 8.6 9.8	W W W	23.2 21.5 27.1	160 95 135
Burro Test 1980 [321]	3 7 8 9	B D E D	5.6 8.8 1.8 5.9	L L L L	88 99 117 136	167 174 107 79
Coyote 1981 [36]	3 5 6	B-C C-D D	6.8 10.5 5.0	L L L	101 129 123	65 98 82
Falcon 1987 [20]	1 3 4	G D D-E	1.2 3.7 4.3	L L L	202 133 61	131 154 301

The US Department of Energy Report 2012 [322] considered 0.005 m^2 (80 mm diameter) as a very small breach size in studying the impact of LNG spill. According to Fitzgerald [250] the oil and gas industry has generally adopted the 2 inch (50.8 mm) maximum leak size for Facility Siting Studies (FSSs) and guidance relevant to leak size also tends to agree in either limiting leaks to a maximum diameter of 2 inches or uses a portion of the pipe cross-section as their assumed leak size. This has been considered as the accepted level of conservatism in most facilities. This shows that these leaks sizes, or smaller, are often not considered in risk analysis and their prevention or control strategies are not emphasised. However, typically smaller leaks (10-25 mm) are highly likely to occur in the LNG facility's lifetime [15]. A fugitive leakage often represents only a small source of leaks and seems to be inconsequential. However, if the leaked fuel is exposed to an ignition source within its flammable range, it will cause various transitional events in congested layout leading to catastrophic consequences. According to an HSE report [42], more than 50% of the total hydrocarbons (HCs) release incidents are minor ones (Table 4-2). On the other hand, an accumulation of several fugitive leakages from any source, or group of sources, creates a major release into the air which is equivalent to a large release. Given the high frequency of small leaks and the high potential to trigger major accidents, smaller leak and its dispersion may be too simplistic to ignore. Despite the high frequency of small leaks and potential for major accidents, dispersion of gas or LNG leaked from small leak sizes (smaller than or equal to 2-inch) has not been emphasised considering the effect of congestion levels on source terms and LNG vapour dispersion. According to Paris [323] the strength of a gas explosion depends on various variables such as congestion, fuel types, flammable cloud size, shape and ignition location and strength. Equipment congestion plays a critical role in the gas dispersion and explosion [324, 325]. Because equipment congestion changes Lower Flammability Limit (LFL) distance and concentration level [41]. According to the Yellow Book [326] the percentage of the vapour cloud varies, depending on different factors, including the type and amount of the material released, pressure at release, size of release opening, degree of confinement of the cloud, wind, humidity and other environmental effects. The equipment congestion, obstacle and roughness of the surface affect source term parameters and dispersion behaviour. Cormier *et al.* [41] claimed that wind velocity, obstacles, sensible heat flux, and the released mass affect LFL distance and vapour concentration level. Thus, this study considers the effects of equipment congestion on source terms, namely pool evaporation rate, pool area and evaporation rate per area for spreading pool on a steel plate.

Table 4-2. HCs release incidents and percentage of minor release incidents on the UK Continental Shelf.

Year	**Total HC release incidents**	**Number of minor releases**	**Percentage of minor release incidents (%)**
2007	185	110	59.46
2008	147	93	63.27
2009	179	95	53.07
2010	186	109	58.60
2011	142	82	57.75
2012	105	58	55.24
2013	118	70	59.32
2014	94	47	50
2015	93	50	53.76
2016	104	55	52.88

Modelling of gas dispersion in an offshore facility is generally difficult due to complex geometries and layouts. Contrary to conventional offshore facilities, a floating LNG (FLNG) processing facility is expected to have higher risks of vapour cloud dispersion, fire and explosion due to processing, storage and offloading of LNG and other flammable products in harsh environmental conditions [241]. It is stated by Cataylo and Tanigawa [327] that leaks occur across LNG facilities. Li et al. [328] investigated the effect of safety gap on dispersion of gas releases in FLNG platform and claimed that the safety gap reduces the gas cloud size between adjacent modules. But these studies [328, 329] investigated the LNG dispersion phenomena considering large leak size which is a rare event. Small leaks occur frequently, which can be too simple to ignore in a complex layout due to resulting volume of LNG under ambient conditions and potential to cause serious events. Because of these, there is a need for modelling small leak and dispersion characteristics of LNG in FLNG processing facility for risk assessment and management. The current study aims at investigating small leak and dispersion behaviour of LNG in a typical FLNG processing facility by considering effect of equipment congestion. The result demonstrates that small leak of LNG can create hazardous scenarios for fire and explosion events and reveals that higher degree of equipment congestion increases the retention time of vapour and intensifies the formation of pockets of isolated vapour cloud.

4.2. Release and dispersion modelling

Figure 4-1 illustrates the developed procedure for the dispersion modelling of small LNG leak in a complex geometry. This consists of release scenario development, credibility estimation of release scenario, consideration of various degrees of congestion, CFD simulation and comparison of flammable vapour profile.

In step 1, possible release scenarios based on potential release cases of LNG are identified. This helps to select representative release scenarios which cause the release of hazardous material. Due to the large number of release scenarios, it is usual to consider only a few release cases to represent the entire range of scenarios. The release scenarios can be developed using analytical processes such as hazard identification (HAZID), and Hazard and Operability Study (HAZOP). The parameters related to release scenario have been considered in several studies (examples [330-334]). Pool shape and spreading depend on surface types, pouring conditions, and obstacles [333]. Once the LNG pool is formed, the rate at which vapour is produced is related mainly to the LNG spilled area and the rate of heat transfer to the liquid. The pool area is highly dependent on the local terrain over which the spill takes place [333]. The presence of obstructions such as dyke or bund walls, the roughness of the ground can have a significant effect on pool area and shape [333, 334]. The vaporisation rate depends on the thermal conductivity of the ground, heat transferred from the air, and take-up rates by the air flow over the pool [334]. As LNG vapour dispersion behaviour depends on source terms, all parameters associated with an LNG release scenario need to be carefully considered in the dispersion modelling [334].

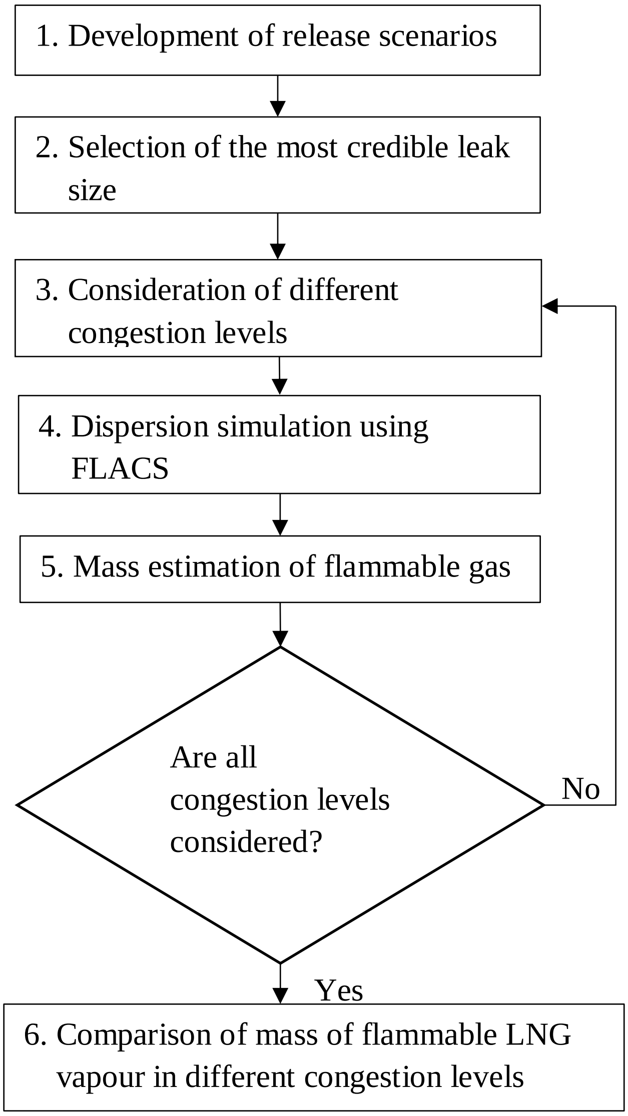

Figure 4-1. Procedure for modelling LNG dispersion using CFD code

In step 2, probable LNG release scenarios are identified according to hazard identification and estimation. The past accident analyses [256, 335, 336] reveal that most of the catastrophic accidents occurred due to ignorance (the accident was unforeseen) and inadequate control arrangements. Thus, it is essential to adequately assess any potential threats/hazards in all areas of a facility foreseeing accident scenario to ensure effectiveness of control measures or emergency plans. The credibility of occurrence facilitates the identification of worse case scenarios and application of effective countermeasures. In a complex processing facility, there can be hundreds of potential release or leak scenarios, hence randomly selecting a few scenarios for modelling is neither appropriate nor reasonable. This makes the credibility estimation an efficient method to identify the most credible scenarios. A credible scenario is one with high probability of occurrence and high damage potential. The damage potential of each scenario is calculated based on hazard identification and assessment. For hazard identification and assessment during release of LNG, several approaches are used, i.e. worst case approaches, maximum credible event approaches and risk assessment approaches [337]. Pitblado *et al.* [254] have identified several maximum credible events including;

a. Maximum credible puncture hole = 0.25 m,
b. Maximum credible hole from accidental operation events = 0.75 m,
c. Maximum credible hole from terrorist events = 1.5 m (1.7 m^2),
d. Maximum credible operational spillage events (10 minutes) = 7,000 m^3/hr, and
e. Maximum credible sabotage event (60 minutes) = 10,000 m^3/hr.

In step 3, various parameters that directly affect dispersion simulation are identified and defined. In semi-confined areas, gas dispersion depends on several factors such as wind speed and its direction, equipment congestion, mass flow rate and atmospheric conditions. In several literatures [41, 338, 339], the impact of wind speed and its direction, mass flow rate and atmospheric conditions are commonly included. However, the impact of congestion level on dispersion of fugitive gases has not received much attention. Equipment arrangement or congestion is important in any processing facility that handles flammable or combustible materials. Tightly packed equipment increases equipment confinement and congestion and affects operations, maintenance, and emergency responses [236]. In such congested areas, an ignition source would be likely, as opposed to remote areas [248]. The consequences associated with the incidental loss of containment are expected to be less severe in less congested layouts than those with higher level of congestion. For instance, larger spaces between equipment reduce the fire impact on surroundings by decreasing exposure level and the thermal radiation intensity. For explosions, larger gaps between equipment reduce the congestion density which enhances the blast decay. These larger gaps decrease the magnitude of the blast waves and the potential effects on equipment, buildings and their occupants. In the case of toxic release, greater distances help reduce the impact on personnel by increasing diffusion and dilution of the toxic gas or vapour [340]. Degree of equipment congestion is often defined based on Area Blockage Ratio (ABR) and Volume Blockage Ratio (VBR) [341]. ABR is defined as the area blocked by obstacles in relation to the total cross-sectional area, and the pitch, which is the distance between successive obstacles or obstacle rows. VBR is defined as the ratio of the volume occupied by congestion elements such as pipes, beams and plates to the volume of the portion of the plant under consideration. Kinsella [342] defined congestion as the fractional area in the path of the flame front occupied by equipment, piping, fittings and other structures such as buildings and supporting columns. If congestion is more than the threshold of 30%, it is considered ‘high’ for an offshore oil and gas facility [343]. Baker et al. [344] have suggested the following definitions of degree of congestion:

- Low congestion: ABR <10%, obstacles widely spaced, <3 layers of obstacles
- High congestion: ABR > 40%, obstacles fairly closely spaced, ≥3 layers of obstacles
- Medium congestion: Between low and high

In step 4, CFD simulation of the most credible leakage and dispersion scenario is performed considering plausible environmental conditions. The CFD model helps to determine the dispersion of the LNG vapour cloud in response to wind-vapour interaction, including heat transfer from the air and ground to the vapour cloud. This can inherently account for the effects of complex geometries, layouts and equipment, and also can assess the effect of vapour barriers on cloud dispersion [318]. For CFD simulation in the current study, FLACS software is used. FLACS has been the leading tool for explosion consequence prediction in petrochemical installations for more than a decade and it is approved for LNG Vapour Dispersion Modelling under US Federal Regulations (49 CFR 193.2059) [345]. Using a finite volume method, FLACS solves the conservations of mass, momentum, enthalpy, and mass fraction of species, closed by the ideal gas law represented by the general Equation 4-1 [261].

$$\frac{\partial}{\partial t}(\rho\emptyset) + \frac{\partial}{\partial x_j}(\rho u_i\emptyset) - \frac{\partial}{\partial x_j}\left(\rho\Gamma_{\emptyset}\frac{\partial}{\partial x_j}(\emptyset)\right) = S_{\emptyset} \qquad (4\text{-}1)$$

Where t, ρ, u and $\emptyset$ represent time, density, velocity and general variable.

FLACS has been extensively validated against different dispersion experiments including Coyote series (3, 5 and 6), Burro tests (3, 7, 8 and 9), Falcon Tests (1, 3 and 4), Maplin Sand Test series (27 and 34) and Thorney Island Tests (45 and 47) [346].

In step 5, flammable vapour footprint is estimated using a concentration range of 2.5-15%. Estimation of flammable mass of dispersed vapour is needed to estimate fire and explosion hazards. In order to cause fire and or explosion, the concentration of LNG vapour should be within the flammability range (5 - 15%) [347]. However, for computing safety distance, the U.S. Federal Government regulation 49-CFR-193 (Flammable vapour-gas dispersion protection) recommended using 50% of LFL. This recommendation has been done to account for two potential effects during vapour dispersion [348]. Firstly, wind may break away pockets of flammable vapour from the continuous cloud and they may be carried beyond the continuous cloud. Secondly, there is the potential expansion of the area of combustion attributed to expanding gases and the high energy release overdriving the flammability limit. Thus, a conservative estimate of the downwind flammable distance is considered by assuming that the vapour pocket will dissipate when the cloud concentration is below half the LFL. Due to these assumptions the resulting cloud coverage length should be considered worst-case possibility [348].

In the final step, flammable mass or volume of LNG vapour is estimated against different congestion levels and dispersion characteristics of fugitive LNG being assessed. Identification of a hazardous region in a facility would help to better understand the requirement of leak detection design and monitoring and control measures. It also would help to identify potentially safer areas during fugitive leaks at given atmospheric conditions.

4.3. Application of the modelling procedure (A case study)

The case study and analysis presented in this paper represents a generic solution method for simulation of vapour dispersion from an LNG spill in a facility with various degrees of equipment congestion. The proposed methodology is applied to a generic layout of a processing facility as shown in Figure 4-2. The model is 160 m long, 60 m wide and 40 m high. Responses to leak, vaporisation and dispersion depend on several operating parameters. For illustration purposes, only a specific case was presented considering prevalent conditions.

4.3.1. Development of release scenarios

In an FLNG processing facility, LNG is present in liquefaction module, storage tanks, offloading system and their connecting pipes. As the main objective of this study is to assess the dispersion phenomenon of fugitive leakage of LNG, a typical small leakage under operational conditions is considered. In chemical processes, fugitive emissions result from equipment leaks, solvent transfers, filter changes, and spills [349].

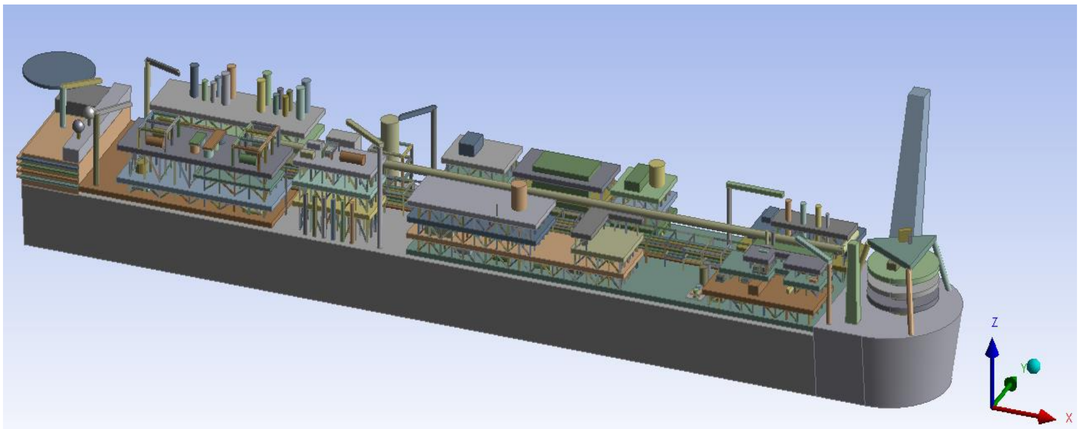

Figure 4-2. A typical FLNG processing facility

For dispersion modelling, the most congested module is considered as shown in Figure 4-3 with the dimensions of 60 m × 45 m × 5 m. This layout is the lowest deck of a module which includes a greater amount of processing equipment than other modules. To assess impact of equipment congestion during LNG dispersion, three different layouts of equipment are considered as illustrated in Figure 4-3. In this study, the equipment layout of the three congestions are derived considering a strategy to reduce vapour turbulence. LNG vapour dispersion depends on source terms (examples: leak rate, pool area and evaporation rate) [334]. The detailed study of source terms is beyond the purpose of the study. However, in this study source terms are incorporated with a careful consideration of the recommendations given in FLACS user's manual [261].

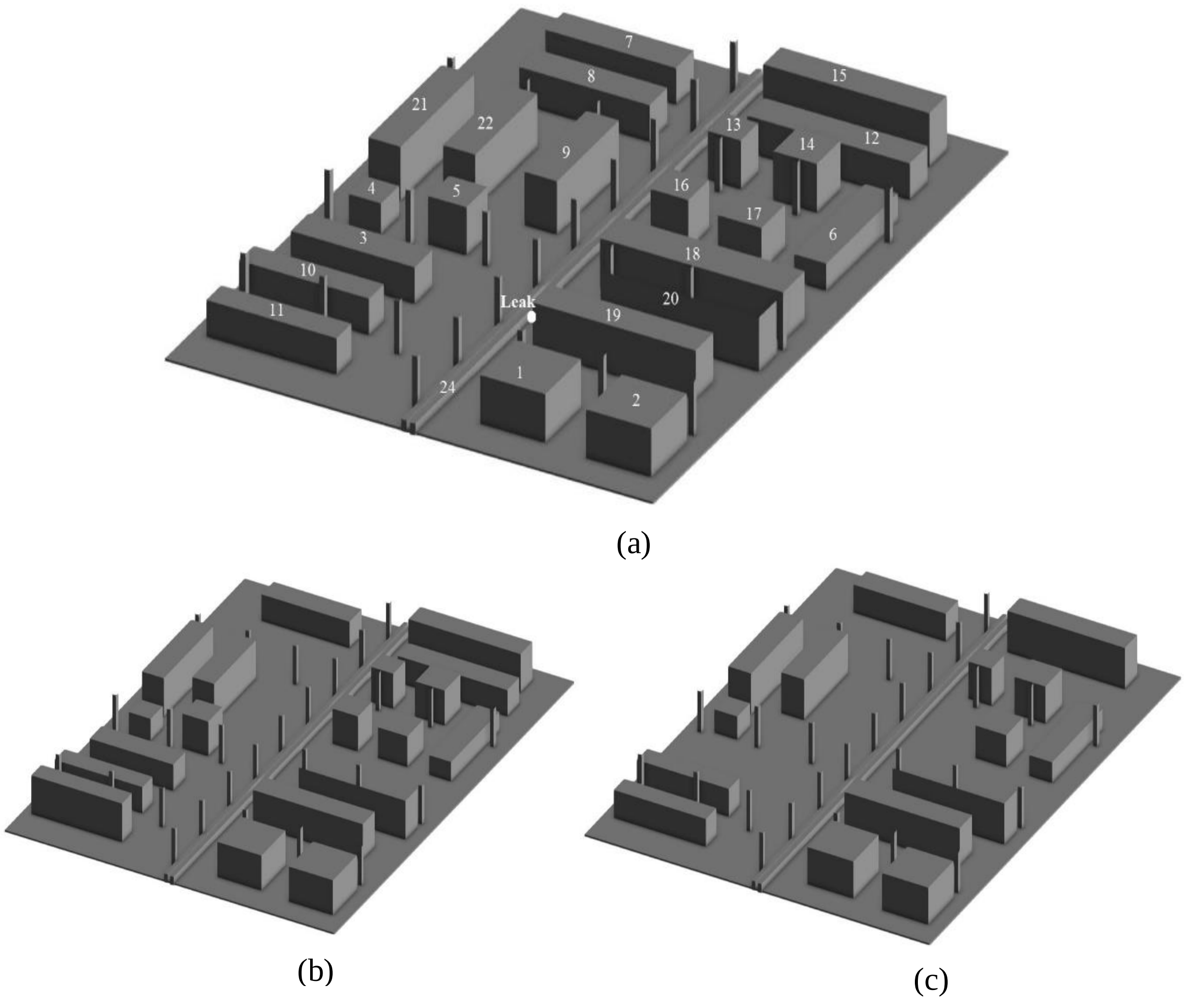

Figure 4-3. Equipment layout in the three congestions based on VBR; (a) 22%, (b) 18% and (c) 14%.

4.3.2. Selection of credible leak size

In a complex processing facility, there can be several potential LNG release scenarios [51]. Generally, in such large facilities, non-hazardous areas are ignored or not given due attention for risk assessment and mitigation because few or no accidents have been reported in such areas. In such situations, even a small leak may lead to a catastrophic accident. There is no universal consensus regarding the credible fugitive leak size. The maximum credible event (leak size/hole) proposed/identified by Pitblado *et al.* [254] contradicts Woodward and Pitblado [15] which stated that smaller leak size of 10-25 mm are highly likely to occur in an LNG plant lifetime. However, it has been found that 2 inch (50.8 mm) leak size is adopted as the maximum permissible leak in oil and gas industry in determining maximum credible events for Facility Siting Studies [250]. This study aims to assess dispersion behaviour of LNG using permissible leak size to investigate potential hazards for fire and explosion. In this study, LNG leak from a puncture hole of 25 mm is considered as the maximum credible size which is 50% less than the maximum permissible leak. Additionally, after release, LNG shows different phenomena of vaporisation and dispersion than that of natural gas due to rapid phase change and volume. This signifies the need to study small leakage of LNG.

4.3.3. Degree of congestion level

Degree of equipment congestion is a pivotal part of safety management. The volumetric congestions calculated in the three layouts are presented in Table 4-3. The first column shows the equipment number according to Figure 4-3 (a). Equipment congestion along the flow front of the vapour is used to determine its effect on dispersion. Columns 2, 3 and 4 represent VBR in cases 1, 2 and 3 respectively. To compare the potential impact of fugitive emission of LNG in different levels of equipment congestion and confinement, three levels of equipment congestion are considered: 22%, 18% and 14%. In this case study, three congestion levels are considered mainly for illustrating the effect of equipment congestion on the dispersion behaviour of LNG. However, any number of congestion level can be considered in this methodology to analyse the dispersion behaviour against the effect of equipment congestion. Dispersion characteristic of small leakage of LNG is assessed based on the mass or volume of combustible vapour in each layout.

Table 4-3. Calculation of equipment congestion in the three layouts.

Equipment	**Case 1 (m^3)**	**Case 2 (m^3)**	**Case 3 (m^3)**
1	90	90	90
2	90	90	90
3	108	108	-
4	21.20	21.20	21.20
5	38.47	38.47	-
6	108	108	108
7	90	90	90
8	90	-	-
9	108	-	-
10	108	108	108
11	135	135	135
12	135	135	-
13	28.26	28.26	28.26
14	50.24	50.24	50.24
15	126	126	126

16	28.26	28.26	-
17	43.96	43.96	43.96
18	240	-	-
19	180	180	180
20	192	192	192
21	144	144	144
22	144	144	144
23	23.84	23.84	23.84
24	30	30	30
Total volume	2352.22	1914.22	1514.50
Congestion levels based on VBR	22%	18%	14%

4.3.4. Dispersion simulation using FLACS

Dispersion of LNG vapour is greatly influenced by local atmospheric conditions, wind speed, atmospheric stability, and ground roughness. For an accurate dispersion simulation using CFD code, a precise representation of boundary conditions, initial conditions and atmospheric parameters are important. It is assumed that the gas cloud releases instantaneously and disperses under ambient atmospheric conditions considering the presence of the obstacles. Defining boundary conditions is a key player in an accurate CFD simulation [284]. According to Luketa-Hanlin *et al.* [285], seven boundary conditions are required for an LNG simulation: inlet, outlet, top, two sides, bottom, and LNG pool. In all three layouts, the same boundary and initial conditions are used. The lower boundary in x-axis, the upper boundary in y-axis and upper boundary in z-axis are assigned as wind (inflow or parallel boundaries). The appropriate wind speed for flammable cloud dispersion is usually close to 2 to 4 m/s [341]. Thus, wind speed is considered as 3 m/s diagonally in the direction of 225 ° to allow for maximum interaction of the dispersed gas with equipment. The reference height of the wind is considered as 2 m. In these boundaries, relative turbulence intensity and turbulence length scale are assigned as 0.1 and 0.014 m respectively, based on recommendation given in FLACS user manual [261]. The remaining boundaries, except the bottom boundary, are considered as nozzle at the outflow). The outlet boundaries are kept sufficiently far from the potential natural gas cloud build up location to avoid their effects on dispersion phenomena. Initial conditions assigned for the simulation are provided in Table 4-4. To reduce uncertainty in this study, value of sensitive parameters such as wind speed, atmospheric stability and release rate have been chosen according to past studies [41, 350-352].

Table 4-4. Initial conditions used for the current study

Parameters	**Values**
Characteristic velocity	3 m/s
Relative turbulence intensity	0.1
Turbulence length scale	0.014 m
Temperature	20 °C
Ambient pressure	100 kPa
Ground roughness	0.01 m
Reference height	2 m
Pascal class	F

It is assumed that the LNG vapour consists of 92% methane, 7% ethane and 1% propane [261]. Release scenario depends on various parameters, i.e. leakage velocity, leaked size and type of surface. The leakage parameters are given in Table 4-5. It is assumed that a leak commences after 10 s so that the wind field can reach steady state before the occurrence of the leakage. A constant mass flow rate of 3 kg/s is considered with an effective leak diameter of 0.025 m based on small leak characteristic [15, 353]. In each simulation, the maximum simulation time is considered as 120 s and the leak stops at 80 s. The release duration and the simulation time has been selected considering Emergency Shutdown (ESD) response time and response time of gas detectors. This duration is confirmed by offshore personnel. These values are also similar to those reported in the literature [354, 355]. According to Napier and Roopchand [356], release duration from dock manifold area (nozzle/line discharge rate) failure is 1.5 minutes. Based on this, the release duration has been chosen. The focus of the case study was to primarily demonstrate the various steps of the release and dispersion modelling approach. However, this duration can be changed to any field scenario.

Table 4-5. Leak parameters

Leak type	Jet
Leak position	(25.57, 16, 1)
Leak direction	-X
Start time	10 s
Duration	80 s
Outlet a. Area b. Mass flow rate c. Relative turbulence intensity d. Turbulence length scale e. Temperature f. Surface	 0.005 m^2 3 kg/s 0.02 (Low) 0.025 m -162°C Steel plate with thickness of 0.01905 m

The simulation volume is considered as 47 m × 62 m × 5 m with maximum grid size of 1 m in all directions. Around the leak location, the grid resolution is adjusted to 0.01 m in x, y and z directions while at the locations far from this area, grids were stretched. The total number of control volumes during the dispersion simulation is 319,200. Setting up the required parameters, the FLACS solver (dispersion and ventilation module) was used to run the simulation. To make the simulation results grid independent, sensitivity analysis was conducted by comparing gas concentrations at a monitoring point using the technique advised by GexCon AS [261].

4.3.5. Estimating mass of flammable LNG vapour

The total mass of the released LNG is 240 kg which is the same in all simulations. However, this value does not represent the actual mass of flammable vapour as an entire mass of released LNG is not within the flammable range. All released mass of LNG does not remain in flammable concentration. The fraction of the released mass within the flammable range is estimated using a utility program of FLACS post processing results. The maximum vapours with 2.5-15% concentration obtained in the three simulations at 2.3 m above the ground are illustrated in Figures 4-4 – 4-6. In this study, the location of the flammable concentration is observed clearly in 2D figure. Thus, 2D figures are used for showing the footprint for the flammable concentration after the leak is stopped. The size of vapour clouds was clearer in 3D figures than 2D. Therefore, 3D figures are used for illustrating the dispersed cloud because the cloud represents the area of interest for subsequent fire and explosion event perspectives. Under the given conditions, volume and mass of flammable vapour dispersed (available) in the three layouts are estimated using post processing results of simulation as shown in Table 4-6. The flammable mass is the mass of the fuel when the ratio ((fuel mass)/(fuel and air mass)) is within the flammable range (2.5-15%). Thus, the flammable volume consists of the mixture of fuel and air. The likelihood of vapour ignition outside the given range at the given time is considered negligible.

Table 4-6. Mass and volume of flammable vapour in the three layouts.

Congestion levels	Case 1 (22%)	Case 2 (18%)	Case 3 (14%)
Maximum flammable mass of vapour (kg)	9.53	3.52	2.05
Maximum flammable volume of vapour (m3)	218	84	45

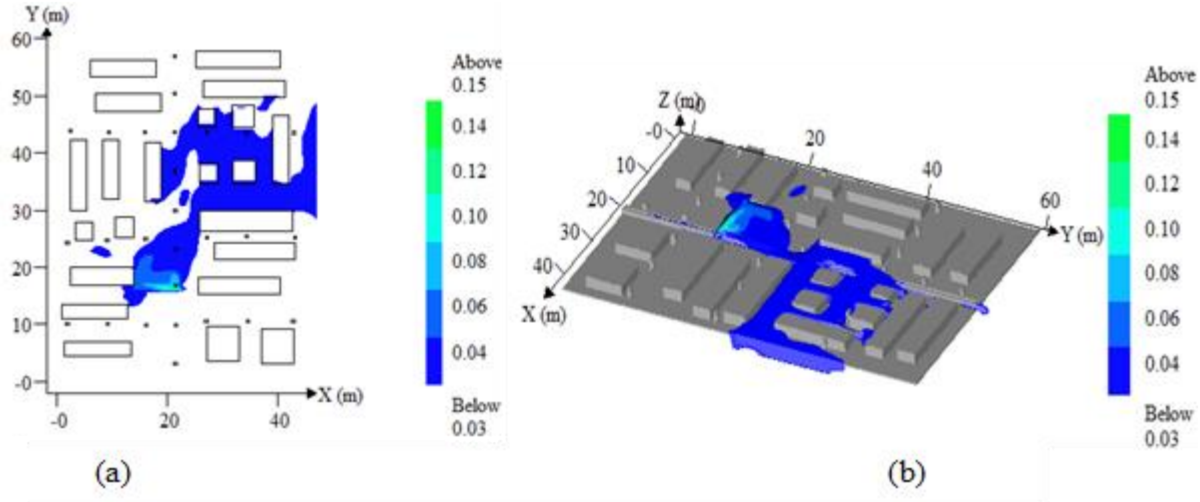

Figure 4-4. Footprints of flammable vapour (m^3/m^3) at 2.3 m above the ground in Case 1 (a) 2D and (b) 3D at 90 s. The concentration range is selected to assess the presence of the flammable vapour in the layout.

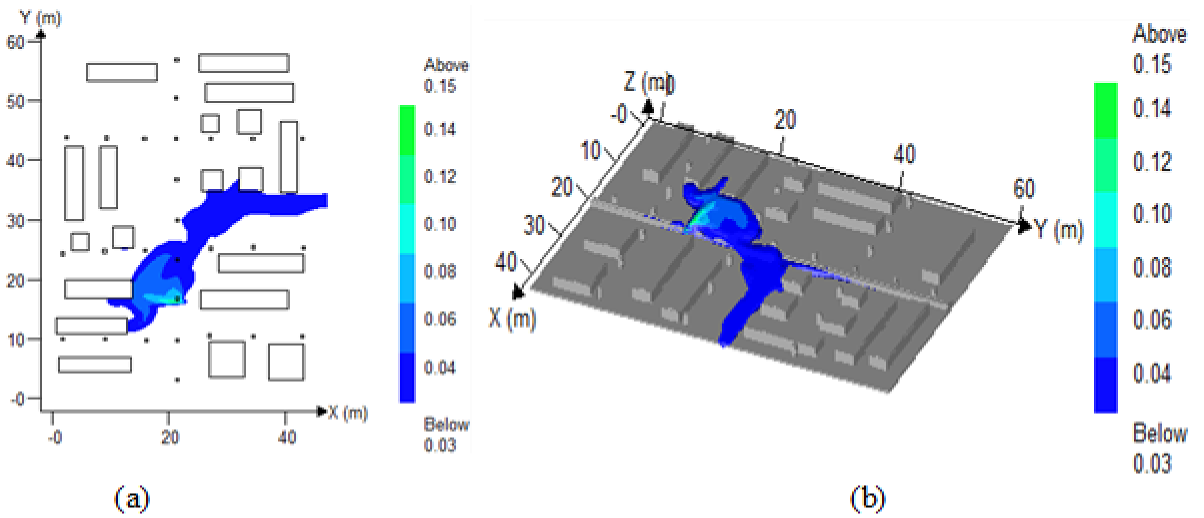

Figure 4-5. Footprints of flammable vapour (m^3/m^3) at 2.3 m above the ground in Case 2 (a) 2D and (b) 3D at 90 s. The concentration range is selected to assess the presence of the flammable vapour in the layout.

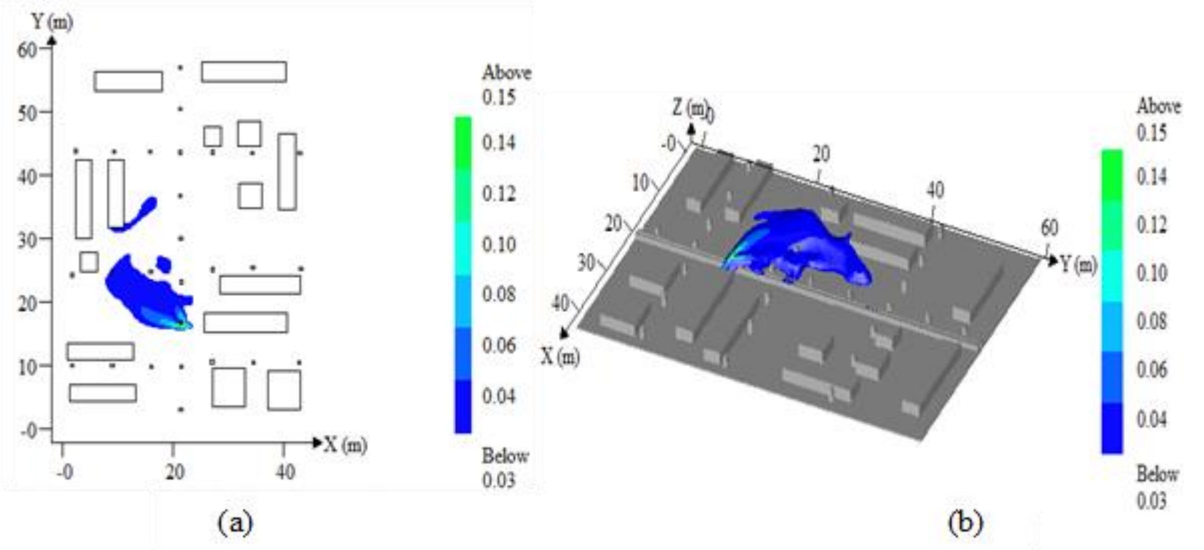

Figure 4-6. Footprints of flammable vapour (m^3/m^3) at 2.3 m above the ground in Case 3 (a) 2D and (b) 3D at 90 s. The concentration range is selected to assess the presence of the flammable vapour in the layout.

4.4. Results and discussion

The most important parameter for dispersion is the footprint of flammable vapour in the air within the layout. To be ignited, the fuel vapour formed through the dispersion should be in the flammable range. The vapour mixture has an LFL of 0.05 and an Upper Flammability Limit (UFL) of 0.15. Considering the safety margin, advised by the US Federal Regulation 49 CFR Part 193.2059 [304], the LFL is defined as 0.025. The effect of congestion level on the formation of flammable vapour was analysed by monitoring the dispersion characteristics. In each case, the areas outside the boundary of the vapour are non-hazardous at that time because in those areas LNG vapour is not in the flammable range. In this study, the potential fire and/or explosion hazard of small LNG leak is assessed considering both time dependent concentration analysis and area-based model which focused on the maximum damage area because a flammable cloud takes some time to develop before reaching its maximum value and the ignition can occur anytime and anywhere after the release. Hence, a given leak can lead to several explosions or fire scenarios depending on the cloud size at the time of the delayed ignition. Thus, this study considered interactions between congested regions and drifting clouds or gas cloud built-up from pool evaporation. A concentration plot at any given location as a function of time is helpful to determine the need of safety measures such as forced ventilation or vapour barrier and to analyse subsequent fire and/or explosion hazards.

4.4.1. Case 1

The first level of congestion considered in the current study is 22%. The LNG vapour tends to slump in the congested layout due to low air movement, after vaporisation of LNG as demonstrated in Figure 4-7. The exact location of the leak is marked with red circle in Figure 4-7 (ii), which is same in Figures 4-8 and 4-9. The maximum flammable mass and volume are 9.53 kg and 218 m^3, respectively at 40 s. The presence of an obstacle in the centre of the flow path diverted the flow front and pockets of vapour accumulated around equipment. In addition to this, the presence of obstacles in the flow path diverted the flow and vapour was distributed in the spaces between obstacles. This allowed the vapour to remain in the layout for a longer time which increased the cloud size. The LNG vapour dispersed according to wind direction and entrained around obstacles leading to formation of pockets of vapour concentration in isolated locations. The leak stopped at 80 s and the hazardous vapour remained in the layout until 120 s as shown in Figure 4-7. This increased the retention time and the likelihood of ignition of flammable hazard. This also points out how important it is to consider the appropriate flammable range in a safety design of such processing plants. One may only consider the regular value of 5% which shows a safer layout according to the dispersion results. However, in considering the LFL value recommended by the US Federal Regulation [304], it reveals that the layout is not safe after the release of LNG. If an ignition occurs within 110 s, the vapour could be ignited with catastrophic consequences, i.e. flash fire in the case of immediate ignition or Vapour Cloud Explosion (VCE) in the case of delayed ignition. This implies that the 22% level of equipment congestion cannot be considered as a safe level.

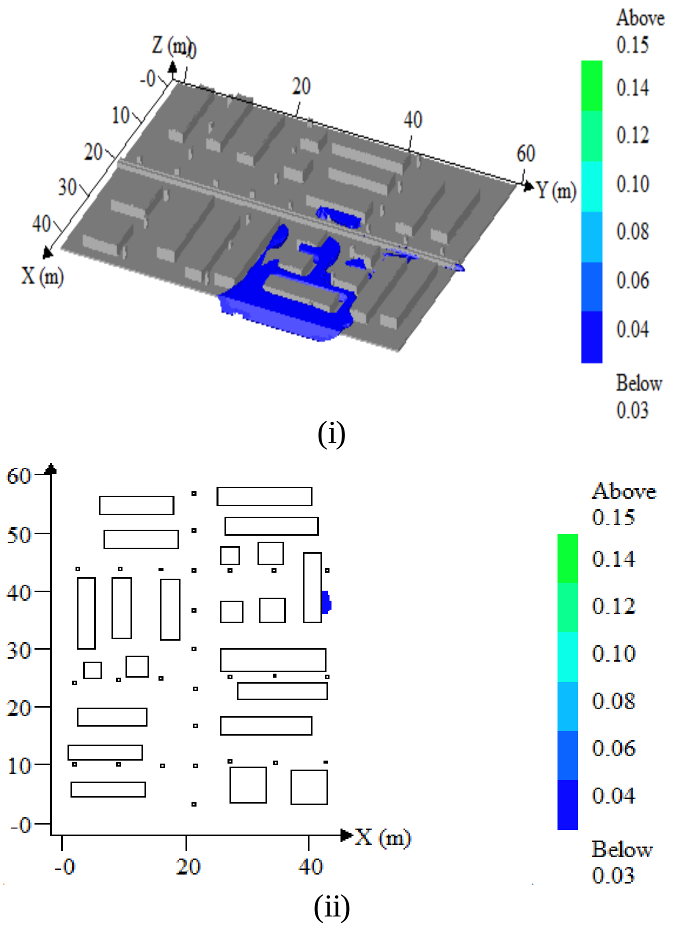

Figure 4-7. Dispersion of LNG vapour in flammable volume concentration (m^3/m^3) at 2.3 m above the ground in Case 1 at (i) 110 s and (ii) 120 s. The concentration range is selected to assess the presence of the flammable vapour in the layout.

4.4.2. Case 2

In Case 2, the volumetric congestion is 18%. The flow paths and vapour size at 100 s is shown in Figure 4-8. The number of obstacles with larger influence in flow diversion in the middle of the flow was reduced. This reduced obstruction in the flow path of the cloud. As a result, the pockets of vapour were not formed, and the vapour path was simply diverted in two directions. The flammable vapour disappeared at 110 s. Although the dispersion analysis shows an improvement in the safety level of the layout with 18% congestion, in this case the ignition of the vapour and flash fire is still a likely scenario.

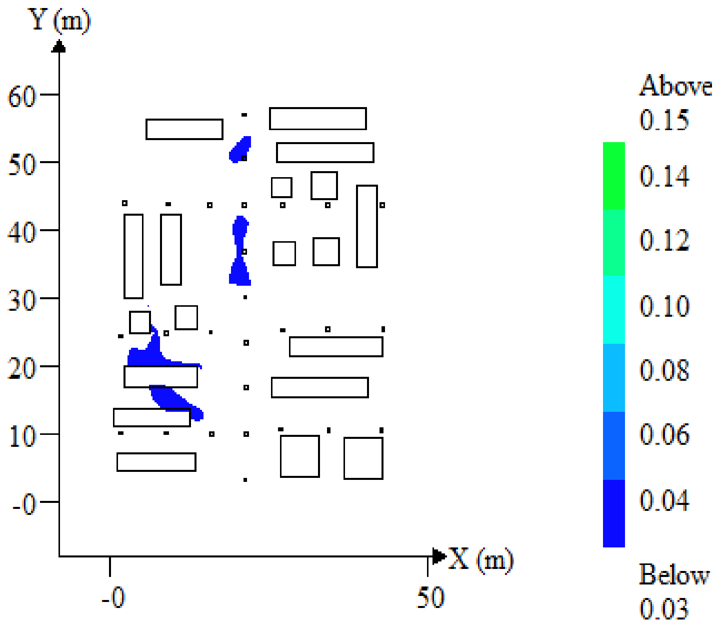

Figure 4-8. Dispersion of LNG vapour in flammable volume concentration (m^3/m^3) at 2.3 m above the ground in Case 2 at 100 s. The concentration range is selected to assess the presence of the flammable vapour in the layout.

4.4.3. Case 3

In this layout, three more pieces of equipment were eliminated from the nearby flow front and 14% volumetric equipment congestion is obtained. The maximum vapour cloud footprint is observed at 78 s. The absence of an obstacle immediate to the leakage area in the flow path resulted in undiverted flow of the vapour as demonstrated in Figure 4-9. The decrease of congestion level facilitated the quick dispersion of vapour leading to the rapid dilution of flammable vapour with it disappearing at 100 s.

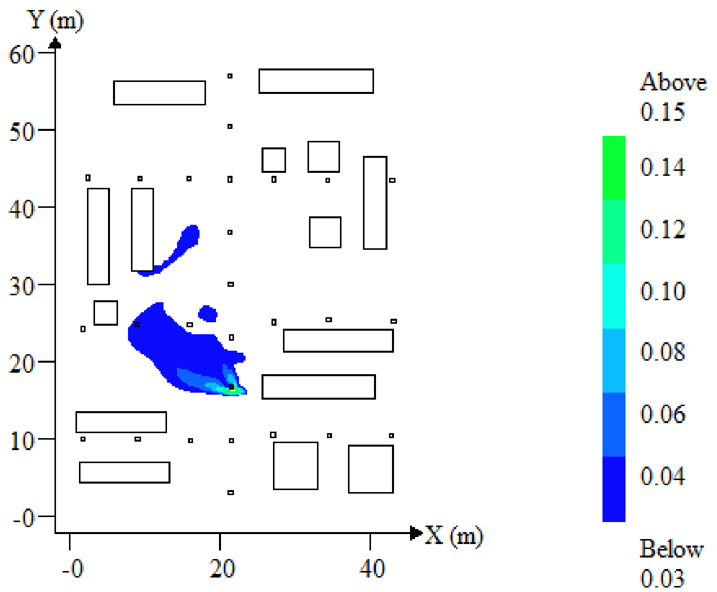

Figure 4-9. Dispersion of LNG vapour in flammable volume concentration (m^3/m^3) at 2.3 m above the ground in Case 3 at 90 s. The concentration is selected to assess the presence of the flammable vapour in the layout.

The flammable mass of LNG vapour in three cases at different times is presented in Figure 4-10. The flammable mass of LNG vapour is estimated using an inbuilt utility program of FLACS post processing result. The total mass of flammable material released as a function of time was calculated and determined the flammable mass in a vapor cloud by integrating across the concentration profiles between two concentration limits, the LFL and the UFL. It is found that under the same conditions, the dispersion characteristics influenced by obstacles have significant impact on the existence of flammable mass and volume in the given layout. There is no significant reduction in the mass and volume of flammable vapour after 10 s of the termination of the leak. In Case 1, flammable vapour remains in the layout until 40 s after the leak ceases and in Case 2, it remains 25 s after the termination of the leak. Similarly, in Case 3, the flammable vapour disappeared after 18 s of the leak stopping. It is confirmed that the retention time of vapour drops with the decrease in congestion level and the formation of vapour pockets depends on obstacles in the flow path. The flammable concentration does not disappear promptly after stoppage of the leak; however, it gradually decreases within different time ranges which depend on the equipment congestion level. The isolated pockets of LNG vapour formation can remain undetected for certain time intervals. This suggests that in any typical congested or semi-confined areas, such accumulation may exist for a significant time even if the leak ceases.

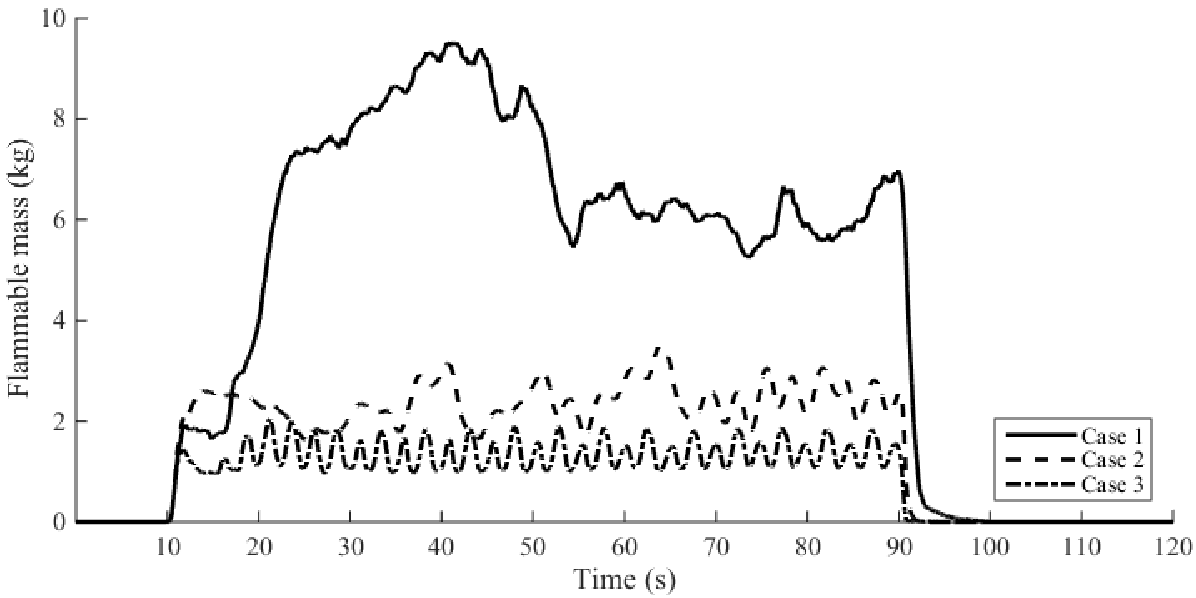

Figure 4-10. The flammable mass of LNG vapour in three cases at different times

Changing the congestion level, even by a small percentage and a change of layout, can produce different vapour flow front and vapour cloud shape under the same environmental conditions. Furthermore, it is observed that mass and volume of flammable vapour in a layout depend on equipment congestion during the fugitive leakage of LNG. The presence of vapour at any instant of time decreases with reduction of congestion level as illustrated in Figure 4-10. This is due to the combined effects of the increased effective contact area and heat transfer rate, and higher vapour dissipation rate than that of high congestion level [334]. For illustration purposes, source terms such as a pool evaporation rate per area, pool area and pool mass for spreading pool on a steel plate are plotted and compared as given in Figures 4-11 - 4-13. These illustrations show that equipment congestion can affect these parameters and subsequently the dispersion behaviour. However, under these considered scenarios, a clear correlation was not obtained due to the lack of uniform variations. As illustrated in Figures 4-11 - 4-13, the time dependent plots in different congestion levels were not same under the same input parameters. Because of this, the effect of equipment congestion and layout on dispersion of LNG seems to be a key factor in assessing and modelling potential vapour dispersion hazards. This also signifies a need for vapour dispersion control strategies such as vapour barriers that can be employed to mitigate potential vapour dispersion hazards in the event of an LNG spill around the safety critical areas.

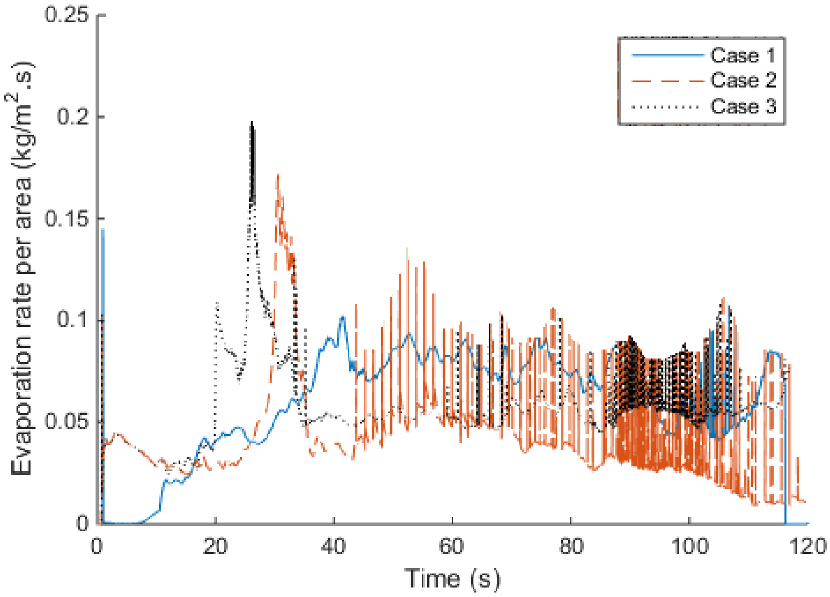

Figure 4-11. A comparison of evaporation rate per area of the LNG pool in three cases.

Often fugitive gas dispersion is neglected assuming that a fugitive gas leak has no potential to cause major accidents and it is difficult to assess its direct impact [357]. It may have no impact, or its impact can be insignificant if the released gas does not ignite or ignites without propagating and transitioning to other events such as explosion event. However, there are many instances where fugitive leaks, dispersions and ignitions have caused catastrophic fire and explosion [358]. It is agreed that heat radiation from the ignition of such a small quantity of gas may not cause direct asset damage, but, has the potential to trigger secondary or tertiary events thereby causing domino effects (chain of accidents). One example of small leak and major accident is the Skikda LNG accident which was initially caused by small leak which ignited and resulted in the first small explosion [300]. This explosion breached the boiler and provided an ignition source to the external accumulation of combustible gas leading to the larger explosion.

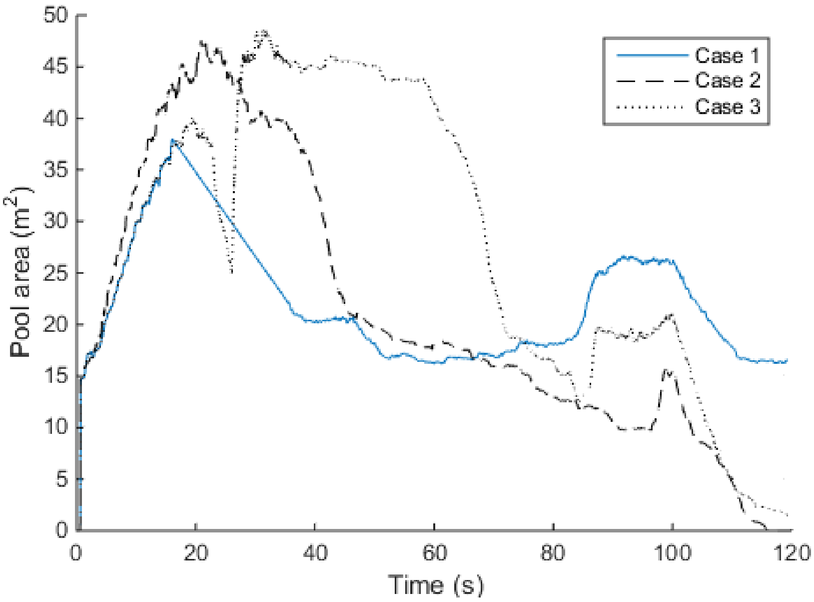

Figure 4-12. A comparison of pool area in three cases.

Besides, fire and explosion hazard, LNG vapour has potential for asphyxiation hazard during an accidental release of LNG. Integration of an asphyxiation hazard analysis with dispersion modelling would help to identify potential impact to personnel in the facility. According to Lipton and Lynch [359], workers frequently exposed to gases from fugitive emissions in processing plants. Even though, the quantity of fugitive emissions is very small, prolonged exposure may be threatening to health especially if carcinogens are involved. Consideration of fugitive emissions from an occupational health viewpoint is essential because each year more people die from work-related diseases than are killed in industrial accidents [357]. Therefore, it is important to reduce fugitive emissions as low as reasonably practicable to create a healthier, safer, more productive workplace as well as improving operating efficiency.

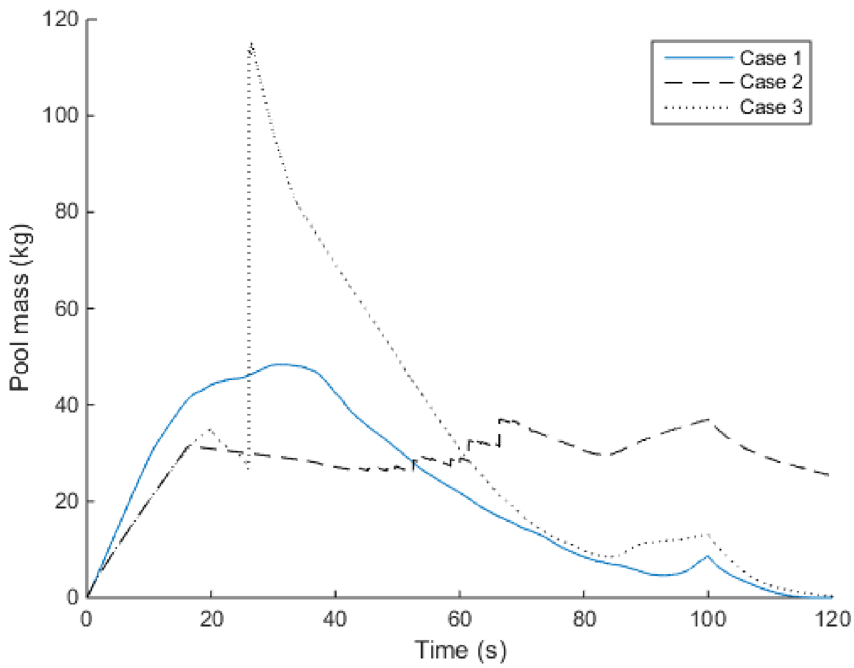

Figure 4-13. A comparison of pool mass in three cases

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For handling uncertainty of various parameters in dispersion modelling, different techniques are available such as Monte Carlo simulation and fuzzy sets theory. In the proposed methodology, uncertainties can be handled by using mean value of sensitive parameters obtained from past studies [350-352]. Uncertainty analysis in dispersion of gas is well discussed in past studies [350-352]. For instance, Siuta *et al.* [350] used fuzzy sets theory and Monte Carlo simulation for uncertainty analysis to model LNG source terms and dispersion models. To reduce uncertainty in dispersion modelling, value of sensitive parameters such as wind speed, atmospheric stability and release rate have been chosen according to these past studies. Moreover, a grid sensitivity analysis was performed using volumetric concentration to obtain grid independence solution. A comprehensive uncertainty analysis was beyond the scope of this study as the main purpose of the case study was to show the application of the proposed methodology. However, a detailed uncertainty analysis can be considered in future work.

4.5. Conclusions

In any congested and complex layout of processing facilities, a fugitive release of LNG would be a major safety concern. A methodology is proposed for modelling a small LNG leak and its dispersion. The methodology comprises of release scenarios, credible leak size, simulation, comparison of congestion level and mass of flammable vapour. The methodology is applied to a typical layout considering three levels of equipment congestion. The potential fire and/or explosion hazard of small LNG leak is assessed considering both time dependent concentration analysis and area-based model. The case study demonstrated that even after the termination of the leak, the LNG vapour continued to disperse, and the volumetric concentration was still within the flammable range. This led to accumulation of pockets of LNG vapours in the spaces between equipment. In the higher degree of congestion layout, higher amount of flammable mass and volume of LNG vapour was observed. The retention time of the flammable vapour in the higher congestion level layout was also more than that in the lower congestion level layout under the same operating conditions. Subsequently, this intensifies the formation of pockets of isolated vapour cloud. In a congested layout, the accumulation of flammable vapour of LNG would remain undetected and could pose fire and explosion hazards. It is therefore too conservative to neglect small leak scenario in a complex layout because of the effect of equipment congestion on source terms and dispersion behaviour. The case study results demonstrated that equipment congestion has effects on both source terms and dispersion of LNG vapour. This signifies a need for robust measures for detection and monitoring of such releases, including effective prevention and control measures such as ventilation, vapour barriers and emergency shutdown systems in a congested LNG processing facility. The study also confirmed that in considering 2.5% as lower flammability limit for assessment of hazard distance, as recommended by the US 49-CFR-193.2059 regulation, design safety could be improved. Furthermore, an asphyxiation hazard, likely to be posed by LNG vapour, would be an important aspect of LNG vapour dispersion modelling in future works.

Chapter 5

Fire Impact Assessment in FLNG Processing Facilities using Computational Fluid Dynamics (CFD)

Abstract

Increasing demand for natural gas has pushed the exploration of natural gas to remote offshore locations using a Floating LNG (FLNG) facility. In this facility, fire hazards are comparatively high and even a single fire accident may be catastrophic due to the congested and complex layout of the facility. This study proposes a novel methodology for modelling the impact of a fire event in an FLNG facility. Hazard identification and accident credibility assessment have been used to discover the three most credible fire accident scenarios. These scenarios have been simulated using Computational Fluid Dynamics (CFD) code, Fire Dynamics Simulator (FDS). The results have then been compared to identify the most severe impact of the fire on personnel and assets using thermal radiation and risk levels. It has been found that the fire event in all three scenarios has a high potential to cause damage to adjacent assets. From this comparison, it is evident that the scenario in the Mixed Refrigerant Module in the liquefaction process has the highest risk of fire to both on-board personnel and assets. The proposed methodology may be adopted further for safety measure design to mitigate or avoid the impacts of a fire event in any complex processing facility.

Keywords: CFD, fire modelling, accident credibility, hazard assessment, FLNG

5.1. Introduction

Process facilities are usually equipped with diverse equipment, control systems and operating procedures. Any process deviations from normal operating conditions, due to errors in the interaction of equipment, human factor, management and organizational issues make process plants susceptible to process failures and or accidents [360, 361]. Some major accidents such as the Piper Alpha disaster [11], the Bhopal accident [362], the Ocean Ranger accident [12], the Cleveland accident [242], the Skikda accident [300], the BP Texas City disaster [29] and the BP Deepwater Horizon explosion [13] are examples of such accidents. Some lessons were learned from each accident and safety regulations and designs have been upgraded [363, 364]. Despite upgrading for designs, operating and emergency procedures, previous accidents demonstrate that the processing plants are still vulnerable [365]. Accidents in processing facilities are mainly associated with fire, explosions and toxic product releases [14].

Fire is the most frequent accident in process facilities and in the transportation of hazardous materials [14, 28]. Considering fire and explosion as the potential major accidents, fires account for 59.5% of these accidents in process industries [29]. Because of the frequent occurrences of fire accidents in process facilities, there is always a need for an efficient means of combating potential fire accidents. This can be formulated by proposing suitable preventive measures targeting the likely vulnerable components in a facility. However, this is difficult to identify unless similar past accidents are thoroughly considered and understood. In such situations, accident modelling which relates the causes and effects of events that lead to accidents is required [52]. It supports gathering relevant data and creating realistic scenarios of the accident sequence and summarizing the gathered data into meaningful information [366]. Therefore, in order to assess and manage the risk of fire, appropriate modelling approaches of fire events in different operating conditions are necessary.

In recent years, many studies have been conducted considering the fire risk analysis and accident modelling [367-370]. For modelling the impacts of fire, various models are available, namely semi-empirical models, integral models, zone models and CFD models [367]. Analytical models cannot simulate obstacles and they do not represent the real condition of a system [371]. These models cannot adequately assess smoke emission, toxic combustion products dispersion and visibility, and the time interval which a structure exposed to fire could resist [372]. CFD model is recognized as one of the most powerful tools for identifying the action characteristics of hydrocarbon explosions and fire [373, 374]. In addition, CFD models time-dependent scenarios that could help the users understand and visualize effects of the system under various conditions at different time intervals [371]. The use of CFD model allows for the description of fires in complex geometries incorporating a wide variety of physical phenomena [375]. It can predict the fire behaviour more appropriately than an analytical method [24].

Many researchers used CFD to simulate the potential fire as a part of the risk analysis and accident modelling [373, 376-378]. Kim *et al.* [378] studied thermal diffusion characteristics of the Floating Production Storage and Offloading (FPSO) topside module subjected to the effects of wind speed and direction using CFD. Paik et al. [379] described a number of procedures for the quantitative assessment and management of fire risks in offshore installations and quantified the effects of risk control options such as platform layout, location and number of gas detectors, and isolation of ignition sources. Rajendram et al. [380] modelled jetfire and fireball scenarios using both analytical and CFD approaches and argued that the CFD modelling using the FDS tool provided reasonably accurate results in comparison with the analytical approaches. Jang *et al.* [377] simulated a jetfire, leaked from a pressurised hydrogen pipe rack structure to conduct damage analysis under temperature and heat flux. Jin and Jang [381] conducted fire risk analysis to study heat transfer analysis and non-linear structural analysis of the topside module of FPSO. Dan *et al.* [33] modelled fire accident consequences considering five expansion valve leakages in a dual mixed refrigerant liquefaction process of a Liquefied Natural Gas (LNG) FPSO. Each mentioned research confirms that CFD models have been used widely in a fire event and its consequence modellings.

A Floating Liquefied Natural Gas (FLNG) facility is an emerging technology which is foreseen to be one of the most promising technologies for exploiting remote and stranded offshore gas fields [6]. The FLNG concept is obtained from a mixture of land-based LNG, offshore oil and gas and marine transport industries [7]. In FLNG processing facilities, natural gas is treated, processed, liquefied, stored and offloaded to LNG carriers in the form of LNG. It has economic and environmental advantages without any risks to the public due to its distant offshore location and better security [8]. However, due to compact layouts, motion effects and difficulty of emergency evacuation, rescue, response and preparedness, potential risks to assets and on-board personnel appear to be higher compared to onshore LNG plants of similar capacity [3]. A detailed study of any accident scenarios in an FLNG processing facility is therefore important for risk assessment and management.

Most available research into FLNG processing facilities is focused on hydrodynamics, offloading, layout design and operational challenges of FLNG processing facilities [237, 382-385]. Risk of FLNG operation is higher than conventional FPSO or offshore platforms due to the hazardous properties of LNG including its cryogenic temperature, flammability and vapour dispersion characteristics [13]. These hazards add additional potential safety concerns. Additionally, the increasing complexity of systems may lead to more complex failure modes and new safety issues [12]. According to Aronsson [7], hazardous units in an FLNG facility are cargo handling, gas treatment, liquefaction or regasification, and offloading processes while the main hazards are pool spread and evaporation, rapid phase transitions, dispersion, pool fires and Vapour Cloud Explosion (VCE) [386]. The United States Government Accountability Office [239] has stated that the most likely public safety impact of an LNG spill is heat impact due to a fire. An extensive hazards and consequences description of LNG, including past LNG accident scenarios are discussed by Woodward and Pitblado [15]. The majority of these accidents were initiated by the release of gas or LNG and resulted in fires and explosions. The potential risks of an FLNG processing facility are cryogenic release, fire, explosion and gas dispersion [6]. According to Xie et al. [387], fire in an FLNG facility is one of the most critical risk contributors of all potential risks. Space limitation in an FLNG facility leads to equipment and pipe network congestion and the likelihood of escalation from a relatively small fire is much higher when compared to onshore installations [388].

Most researchers have paid attention to fire scenarios in a particular module or unit of offshore facilities [24, 33, 34] which may not be adequate for fire safety analysis of the whole facility. Moreover, there is no research available, particularly for fire risk and consequence assessment of FLNG processing facilities incorporating credible scenarios in all topside modules. There is a need for a comprehensive study of different fire scenarios in FLNG facilities because of the inherent challenges posed by the operational complexity in a congested space, harsh environment and lack of past experiences or references [35]. Equipment compactness and difficulty in monitoring may make the remaining smaller gas or LNG leaks undetectable. Even the release of smaller quantities of gas or LNG may cause severe impacts upon ignition causing a fire or VCE.

In complex and large facilities such as FLNG processing facilities, there can be hundreds of probable fire scenarios and randomly selecting a scenario for fire modelling may not be appropriate nor reasonable. As there are no past or present experiences of operating FLNG processing facilities, modelling a real scenario may not be feasible at this stage. In order to avoid this limitation, various credible fire scenarios need to be developed and assessed to find the most credible fire accident scenarios. Therefore, this study proposes a methodology to define the most credible accident scenarios and to simulate impacts of fire events in an FLNG facility using CFD. The proposed methodology can be further applied for safety measures designed to mitigate or avoid the consequences of the fire event in complex processing facilities.

5.2. Proposed methodology

This study incorporates development of various plausible fire accident scenarios, damage potential estimation in each scenario, selection of the most credible accident scenario and the CFD simulation to determine the impact of each scenario. The results of the CFD simulation are adopted to analyse the impacts on personnel and adjacent assets and structures. The overall framework of the methodology developed in this study is explained in Figure 5-1.

The first step in the proposed methodology is developing various credible fire accident scenarios in an FLNG facility. According to Mansfield [389], the basic objectives and approaches to safety case formulations are the same for onshore and offshore installations. However, due to complexity, compactness and relative isolation, a more thorough analysis of potential hazards and escalation paths is needed. In an offshore processing facility such as an LNG FPSO, unfavourable events that may escalate to loss of containment are; gas leak from feed gas, vapour, liquid leak from LNG cold box area, gas or liquid leak from refrigeration circuits, external fire in refrigeration circuits, leak from LNG tank, gas evolution from LNG tank rollover, liquid spill from LNG tank instantaneous failure, liquid leak from jetty line failure and liquid leak from loading arm connection failure [15]. As natural gas or LNG vapour is highly flammable, an immediate ignition will cause either flash fire, pool fire or jet fire, but delayed ignition will cause VCE or boiling liquid expanding vapour explosion (BLEVE) or combination of fires. LNG VCE events are not credible over water, but they need to be considered in specific situations if flammable vapours can drift into highly congested areas containing a large amount of processing equipment and can develop overpressures [254]. In developing different possible fire accident scenarios all physical, chemical, environmental and operational characteristics of the facility need to be considered.

In the second step, more credible fire accident scenarios are identified considering various inherent hazards existing in each scenario. There are various methodologies available for hazard index calculation in chemical process industries. The most notably used approaches are Dow fire and explosion index [390], Mond fire, explosion and toxicity index [391], mortality index [392], the IFAL index [393], and hazard identification and ranking system (HIRA) [360]. Damage radius in each scenario is calculated using the HIRA approach.

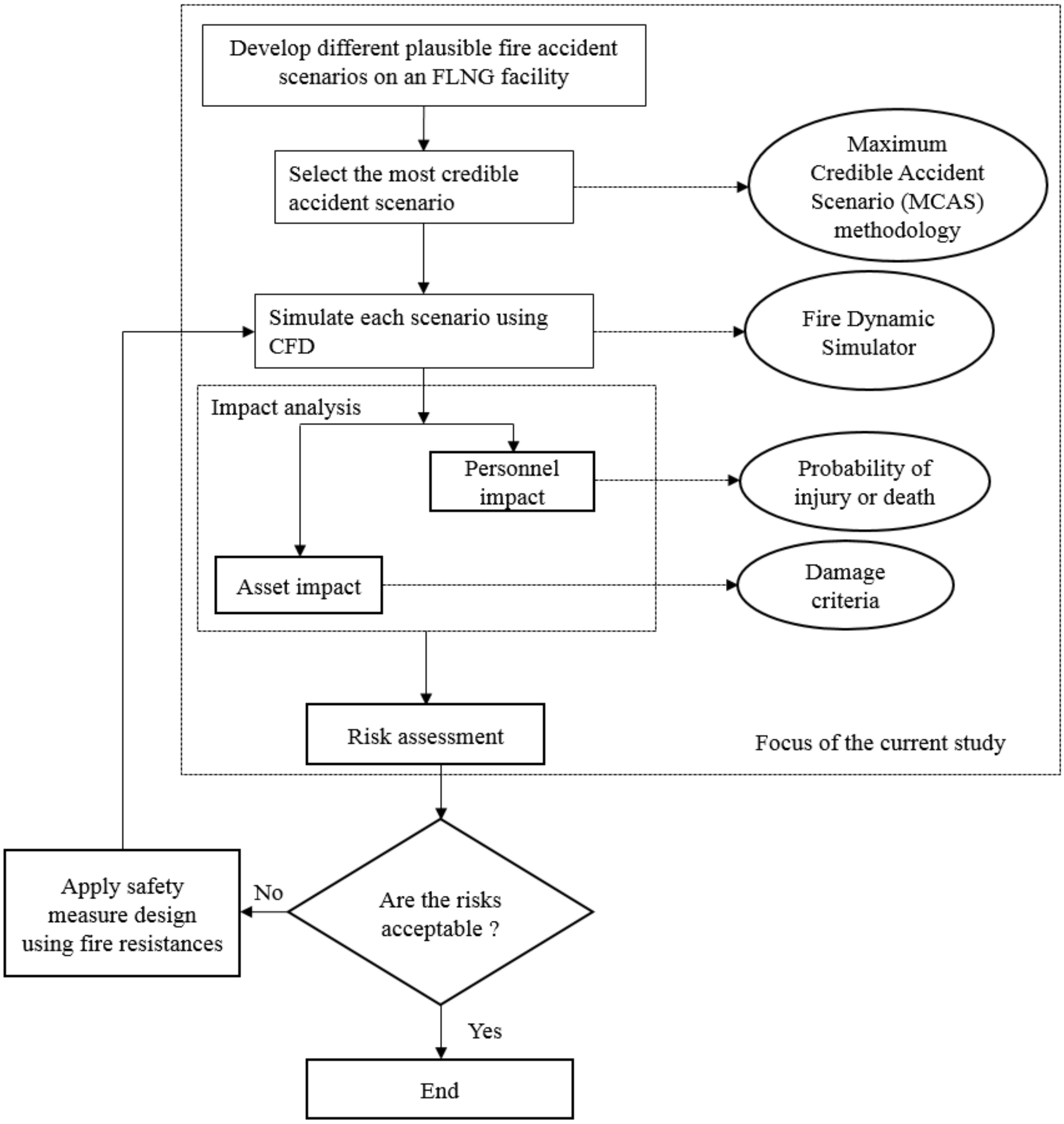

Figure 5-1. Overall framework of the developed methodology of fire impact assessment in FLNG processing facilities.

In credibility assessment of an accident on a chemical process facility, the consideration of the most credible accident scenario is of prime importance [257]. The Most Credible Accident Scenario (MCAS) method proposed by Khan [256] is modified and applied for the credibility assessment of all scenarios. The MCAS methodology is incorporated in this study because it accounts both for probable damage caused by an accident and its probability of occurrence. Thus, it avoids the weaknesses or shortcomings of other methods such as quantitative risk analysis, probabilistic risk assessment, worst case methodology and optimal risk analysis [256].

There may be an accident that occurs frequently but causes insignificant damage. Conversely, there may be accidents that do not occur frequently but cause great damage. A more damaging and frequently occurring accident will have higher credibility. Therefore, an accident with higher probability of occurrence and higher damage potential will have higher credibility of occurrence.

In the third step, CFD simulation of the most credible accident scenarios is performed. Nowadays various modelling techniques or tools for fire accidents modelling are available, varying from simple numerical formulae to complex computational modelling techniques. A CFD model is effective to analyse complicated accident scenarios that empirical models are not capable of [24]. Recently, many studies have been done on fire risk assessment and management, using FDS [54, 376, 380, 394]. The FDS uses a form of the Navier-Stokes equations for low speed thermally driven flow with emphasis on smoke and heat transport from fire. Any turbulence is treated by means of Large Eddy Simulation (LES) [375]. The LES technique is based on the assumption that the numerical mesh is fine enough to allow the formation of eddies.

In this study, the CFD modelling of fire event is performed using FDS codes and the effects of thermal loads and temperatures on surrounding assets and personnel are analysed based on the results of the simulation. The FDS is well validated and verified against different fire scenarios at the National Institute of Standards and Technology (NIST) and beyond [395, 396]. Additionally, the FDS has the capability of simulating fire and smoke development, thermal flow predictions and concentrations of toxic substances released during the fire. The radiation model utilized by FDS [375] is shown in Equations 5-1 and 5-2.

$$\dot{q}_r''' \equiv -\nabla.\dot{q}_r''(x) = k(x)[U(x) - 4\pi I_b(x)]; \tag{5-1}$$

$$U(x) = \int_{4\pi} I(x,s')ds' \tag{5-2}$$

Where $k(x)$ is the absorption coefficient, $I_b(x)$ is the source term, and $I(x,s)$ is the solution of the radiation transport equation (RTE) for a non-scattering gray gas and is explained in Equation 5-3.

$$\mathrm{s}.\nabla I(x,s) = k(x)[I_b(x) - I(x,s)] \tag{5-3}$$

These equations indicate that radiation model with gray gas assumption is considered for the radiative loss term in the energy equation.

In the fourth step, the effects of the fire event are assessed based on human impact criteria and structural or asset impact criteria. The consequences of the fire event to personnel at various distances from the surface of the flame is determined based on the integrated thermal intensity. At different locations, probabilities of having first degree burn, second degree burn and death are calculated using Equations 5-4 and 5-5 [26].

Probit function (Pr) = $c_1 + c_2 \ln D$ (5-4)

The probability of injury or death $(P_i) = F_k \frac{1}{2}\left[1 + erf\left(\frac{Pr - 5}{\sqrt{2}}\right)\right]$ (5-5)

Where D is thermal dose, c_1 and c_2 are probit coefficients and their values are given in Table 5-2, F_k is clothes correction factor and *erf* is the error function. The human effects caused by thermal radiation are given in Table 5-1.

Table 5-1. Effects caused by fire [26, 397]

Effect type	**Damage**
Probability of first degree burn	It affects only the epidermis or outer layer of the skin. The burn site is red, painful, and dry without blisters. Long term damage is rare and usually consists of an alteration of the skin colour.
Probability of second degree burn	It affects the epidermis and part of the dermis layer of skin (0.07 - 0.12 mm depth). The burn site appears red, blistered and may be swollen and painful.
Probability of death	

The impacts on assets are determined based on thermal loads and adiabatic surface temperature of assets during a fire event. Processing facility materials and equipment are susceptible to thermal loads. The main causative factor of asset damage is the total heat load transferred to the nearby units from fire by the combination of radiation and convection. The most vulnerable targets in a process facility are pressurized tanks, atmospheric tanks, process vessels and pipelines [29]. Fires cause structural failure mainly by reducing strength due to heat and thermal stresses [398]. According to World Bank [397], equipment damage occurs at the heat flux of 37.5 kW/m^2 and the minimum heat intensity for ignition and melting of plastic tubes is 12.5 kW/m^2 as given in Table 5-3.

Table 5-2. Coefficients c_1 and c_2 [26]

Effects	c_1	c_2
First degree burn	-39.83	3.0186
Second degree burn	-43.14	3.0186
Death	-36.38	2.56

Table 5-3. Damage caused at different incident levels of thermal radiation [397].

Heat flux (kW/m^2)	**Effects on materials**	**Effects on humans**
37.5	Equipment damage	100% lethality in 1 min. 1% lethality in 10 s
25	Minimum intensity for ignition of wood in prolonged exposure	100% lethality in 1 min. Serious injuries in 10 s
12.5	Minimum intensity for ignition and melting of plastic tubes.	1% lethality in 1 min. First degree burns in 10 s
4		No lethality. 2nd degree burns probable. Pain after exposure of 20 s.
1.6		Acceptable limit for prolonged exposure.

At 538 ^{0}C, the yield strength of A36 steel is approximately about 60% of its yield strength at normal room temperature [398-400]. The American Institute for steel Construction's Specification for the design, fabrication and erection of structural steel for buildings limits the maximum permissible design stress to approximately 60% of the yield strength [401]. Thus, the steel members with 538 ^{0}C are designed to support the maximum permissible stress. Additionally, at this temperature, the modulus of the elasticity of the steel decreases appreciably from its value at normal room temperature [398]. For low carbon steels, significant changes in crystalline structure begin to occur at temperatures of above 650 ^{0}C which is when the steel failure begins [402]. The other factor for structural failure is creep. The rate of creep increases approximately 300 times for ASTM A36 steel when its temperature increases from 460 to 520 ^{0}C [400, 403]. Therefore, at higher temperatures, the yield strength and the modulus of elasticity of the steel decrease and the rate of creep increases significantly. The maximum yield strength and the modulus of elasticity at any elevated temperatures are calculated using the following relationships [400, 404, 405].

For $0 < T \leq 600$ °C,

$$\sigma_{yT} = \left[1 + \frac{T}{900\ln(T/1750)}\right]\sigma_{y0} \tag{5-6}$$

$$E_T = \left[1 + \frac{T}{2000ln(T/1100)}\right]E_0 \tag{5-7}$$

For $T > 600$ °C,

$$\sigma_{yT} = \frac{340-0.34T}{T-240}\sigma_{y0} \tag{5-8}$$

$$E_T = \frac{690-0.69T}{T-53.5}E_0 \tag{5-9}$$

Where

σ_{yT} = yield strength at temperature T (MPa)

σ_{y0} = yield strength at 20 °C (MPa)

E_T = modulus of elasticity at temperature T (GPa)

E_0 = modulus of elasticity at 20 °C (GPa)

Moreover, the most common types of construction materials used in process industries lose 40% of their strength at temperatures higher than 670 K (396.85 °C) and lose 80 - 90% strength at temperatures higher than 850 K (576.85 °C) [406]. Based on these thresholds or impact criteria, the impacts of the fire event are assessed.

In the fifth step, the risks of the fire accident to personnel are estimated by converting the thermal radiation into the corresponding risk profile based on thermal effects as given in Table 5-1 [26, 54, 407]. In order to estimate the severity of risk, the probabilities of first degree burn, second degree burn and death are assigned with risk scores (S_i), as given in Table 5-4. The severity of risk at any location of the facility is calculated by using Equations 5-10 and 5-11 [54]:

Risk score is calculated as $\text{Risk}_i = S_i \times P_i$ (5-10)

Risk of fire = Maximum [$\text{Risk}_{\text{first degree burn}}$, $\text{Risk}_{\text{second degree burn}}$, $\text{Risk}_{\text{death}}$] (5-11)

These risk values represent the overall effects or integrated effects over the whole area around the fire. The risk scores calculated around the three fires are compared in relation to distance from the flame surface.

Table 5-4. Scores for major human impacts caused by fire [54].

Effects	**First degree burn**	**Second degree burn**	**Death**
Score (s)	2	5	10

5.3. Application of the methodology

5.3.1. Scenario development

In order to apply the proposed methodology, a layout design of an FLNG facility as illustrated in Figure 5-2 is considered. 32 different likely accident scenarios are developed to select the most credible accident scenario on the topside of the FLNG facility. These scenarios are developed in a unit or module based on their physical and chemical characteristics [408]. Four different scenarios are developed in a gas treatment facility, including inlet and outlet valves failures or leakages. Similarly, twelve different scenarios are considered in the liquefaction modules. Nine and two scenarios are developed in storage and offloading system respectively. These scenarios are developed based on the vulnerability and the possibility of accidents due to the existence of inherent hazards in these modules [409]. The scenarios considered in this study are depicted in Table 5-5.

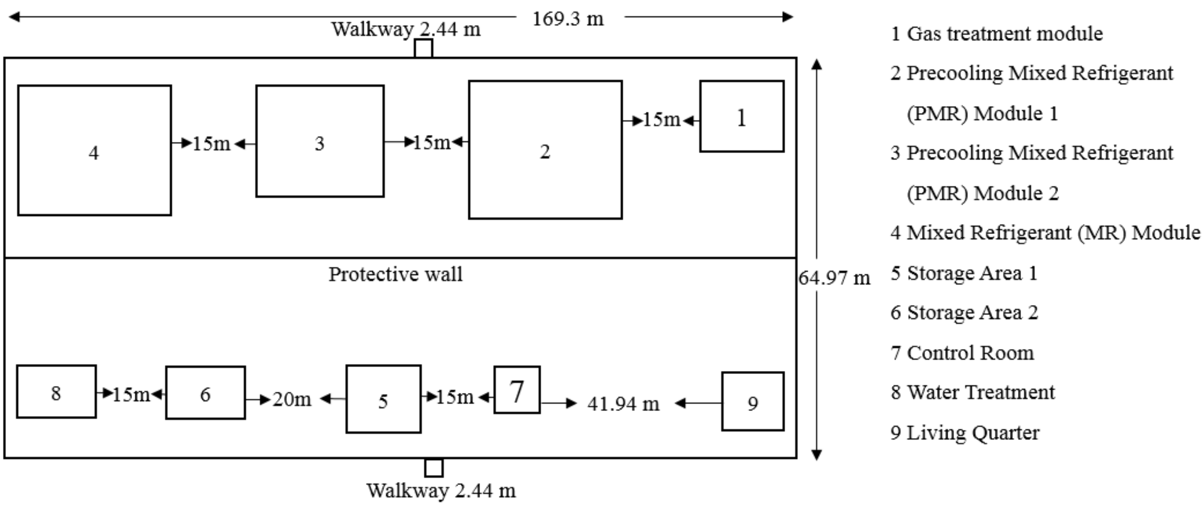

Figure 5-2. Layout design of an FLNG facility [286].

5.3.2. Selection of the most credible accident scenarios

In each scenario, the damage radius (fire and explosion damage index) is estimated by using Hazards Identification and Ranking methodology. This method seems to be more appropriate as it takes into consideration the impact of various process operations with quantitative results. Moreover, most of the penalties used in calculating hazards are derived from the well tried and tested models of thermodynamics, heat transfer and fluid dynamics [360]. In each unit, energy factors and penalties are evaluated and the fire and the explosion damage index is estimated using the damage potential of each unit. The estimated damage radius of each unit or module is used as the damage radius for the accident scenario considered in a particular unit. Using the damage radius and probability of occurrence of accidents, the credibility assessment of each scenario is estimated, and the most credible accident scenario is selected. The probability of occurrence of these accidents is adopted from Kim *et al.* [307] and OPG Risk Assessment Data Directory [409]. Once damage radius and probability of occurrence are known for each scenario, two factors, namely damage to property or assets (A) and fatalities (B) are computed based on the MCAS methodology.

According to the MCAS methodology, the scenarios with credibility values greater than 0.5 are considered as the maximum credible scenario. This means that the scenario will have a higher probability of occurrence and severe consequences. Considering Table 5-5, the three most credible fire accident scenarios in decreasing order of their credibility are as follows;

1. LNG spill due to overfilling or leakage of the tanks and forming a pool in the dike with immediate ignition. The overfilling occurs due to failure of actuators, level alarms and interlocks or failure of outlet valves.
2. LNG liquid leaks under pressure from a 750 mm diameter pipe in Mixed Refrigerant (MR) Module of the liquefaction process formed pool and ignited immediately. This occurs in the pipe that passes LNG to Storage Area 2.
3. Treated two phase hydrocarbon is released under pressure from a 750 mm valve and an immediate ignition occurs with pool fire. This occurs in the pipe that passes two phase hydrocarbon to the Precooling Mixed Refrigerant (PMR) Module 1.

The credibility calculation for the most credible scenario as an example is discussed in Table 5-6.

Table 5-5. Different plausible fire accidents and their credibility.

	Description of scenarios	**Damage radius (m)**	**Frequency of occurrence (per year)[d]**	**Credibility L_{FE}**
1	Untreated gas is released under pressure from a joint with 50 mm hole and the gas is ignited forming a jet fire due to nearby operating pump or motor.	200	3.60×10^{-7}	0.06
2	Untreated gas is released under pressure from a joint with 100 mm hole and the gas is ignited due to nearby operating pump or motor.	350	3.60×10^{-7}	0.20
3	Treated gas is released under pressure from a valve with 500 mm hole and ignition does not occur.	90	3.60×10^{-7}	0.01
4	Treated two phase hydrocarbon is released under pressure from a 100 mm valve and an immediate ignition occurs with pool fire. This occurs in the pipe that passes hydrocarbon to the PMR Module 1.	350	3.60×10^{-7}	0.80
5	LNG liquid leaks under pressure from a 500 mm diameter pipe in MR Module of the liquefaction process and ignited immediately due to static sparks.	300	2.60×10^{-6}	0.75
6	LNG liquid leaks under pressure from a 750 mm diameter pipe in MR Module of the liquefaction process, formed pool and ignited immediately. This occurs in the pipe that passes LNG to Storage 2.	350	2.60×10^{-6}	0.97
7	LNG liquid leaks under pressure from a 500 mm diameter pipe in MR Module of the liquefaction process and formed pools and ignited later.	300	2.60×10^{-6}	0.79
8	LNG liquid leaks under pressure from a 750 mm diameter pipe in MR Module of the liquefaction process and formed pools and ignited later.	350	2.60×10^{-6}	0.75
9	Refrigerant leaks under pressure from a 250 mm diameter pipe in MR Module of the liquefaction process and formed pools and ignited later.	278	3.60×10^{-7}	0.34
10	Precool (-70°C) treated gas leak from a valve with hole diameter 500 mm.	150[c]	3.60×10^{-7}	0.10
		220[b]	3.60×10^{-7}	0.16
11	Precool (-70°C) treated gas leak from a valve with hole diameter 750 mm.	356[c]	3.60×10^{-7}	0.20

		340[b]	3.60×10^{-7}	0.18
12	Two phase vapour liquid leak from LNG cold box area.	278[a]	2.90×10^{-10}	0.00
		350[b]	2.90×10^{-10}	0.00
13	Leakage of pressurised LNG due to dropped objects on the supplying LNG piping networks and immediate ignition causes jet fire.	250	3.00×10^{-6}	0.68
14	Leakage of refrigerants (mainly propane) from the PMR modules and immediate ignition causes a flash fire or jet fire.	353[b]	1.10×10^{-6}	0.54
		100[c]	1.10×10^{-6}	0.05
15	LNG leak from storage tanks at atmospheric pressure due to failure of layers of protection without ignition.	150	8.80×10^{-6}	0.71
16	LNG released instantaneously from storage and immediate ignition caused BLEVE due to knock-on effects.	330	5.00×10^{-7}	0.48
17	An instantaneous release of LNG leads to liquid pools evaporating to form a flammable vapour plume.	150	8.80×10^{-6}	0.71
18	LNG storage tank rollover due to extreme circumstances.	260	6.50×10^{-7}	0.19
19	LNG spills due to overfilling or leakage of the tanks and forms pool and delayed ignition occurs. Overfilling occurs due to failure of actuators, level alarms and interlocks or failure of inlet valves.	260	1.20×10^{-5}	0.99
20	Generation of overpressure in the storage tank (due to failure of relief valve or runaway reaction), causes the tank to fail as BLEVE. The released LNG vapor ignites into a fireball on coming in contact with an ignition source.	260	6.50×10^{-7}	0.26
21	High pressure develops in the storage and LNG releases, though the relief valves. The vapour then disperses in the atmosphere.	150	2.60×10^{-6}	0.13
22	Released LNG evaporates and forms a cloud which disperses to the nearest ignition source and a confined vapour cloud explosion (CVCE) occurs. The released vapors instantaneously disperse into the atmosphere without ignition.	150	8.80×10^{-6}	0.42

23	A slow but continuous release of LNG forms a vapor cloud of relatively lower concentration which on ignition burns as a flash fire.	260	2.90×10^{-10}	0.0000425
24	Release of LNG with high flow rate due to leak in connecting pipe during LNG offloading from storage to carrier, forms a large vapour cloud of high concentration which on ignition causes a vapour cloud explosion.	376	2.60×10^{-6}	0.77
25	LNG spill on seawater and RPT explosion occurs and flash fire occurs due to delayed ignition.	376	2.90×10^{-10}	0.0000893
26	LNG carrier collides with FLNG and causes damage to offloading system, resulting in leakage of LNG.	376	2.90×10^{-10}	0.0000893
27	Fire in Control Module due to electric short circuiting or overloading.	20	1.00×10^{-7}	0.0000867
28	Helicopter accidents near the living quarters with fire and explosion.	20	1.50×10^{-7}	0.000130

[a]Damage radii for pool fire, [b]damage radii for VCE, [c]Damage radii for flash fire, [d]LNG leak frequency is taken from Kim *et al.* [307] and OPG [409].

Table 5-6. Calculation of credibility for the most credible scenario.

Parameters	**Values**
Damage radius	260 m
Area inside the Damage Radius (AR)	212371.66 m^2
Occurrence Probability (PR)	8.8 $\times 10^{-6}$ per year
Asset Density (AD)	\$ 909138.76 /m^2
Unacceptable Financial Loss (UFL)	10^6 (\$/year)
Factor for damage to property or assets (A)	1.70
Population density in the vicinity of fire and explosion	18.18×10^{-3} (persons/m^2)
Population distribution factor for fire and explosion	0.3 (dimensionless)
Unacceptable Fatality Rate (UFR)	0.01 (persons/year)
Factor for fatalities (B)	1.02
Credibility (L)	0.99

5.3.3. CFD simulation using FDS codes

When liquid fuel is released accidentally during overfilling of storage tanks and dikes rupturing pipes and tanks, a pool will be formed on the surface which, vaporizes and upon ignition, results in a pool fire. Pool fire is the most common of all types of fires and the likelihood of occurrence of pool fires on offshore platforms is high due to the continuous handling of heavy hydrocarbons and large liquid inventories [15].

In an FLNG facility, the formation of pool fire occurs mainly due to leaks in LNG storage, liquefaction module and pipe networks. Sikanen and Hostikka [410] modelled and simulated pool fire using FDS and found that the heat transfer within the liquid phase has an effect on the dynamics of the fire but not on the peak burning rate. For pool fire modelling, the most important variable is the wind direction. Other significant factors are the mass flow rate of the spill, fuel properties, maximum burning rate and the boiling point of the fuel [411]. The three most credible accident scenarios are simulated using FDS as it has been already well validated and verified against different fire scenarios and recommended for fire accidents modelling [380, 395, 412].

In each scenario, the simulation volume is considered as 65.5 m × 170 m × 41 m with total simulation time of 46.5 s. The simulation time is taken based on the longest exposure time taken by personnel, with the escape velocity of 1 m/s, to reach designated safe location.

According to Pitblado *et al.* [254], the maximum credible hole from accidental operational events is 750 mm. The flow rate of LNG is calculated considering 750 mm and 2 m/s as the diameter of the leak hole and flow velocity respectively. The release duration is 20 s and the thickness of the pool is considered as 0.2 m. In many pool spread models, a circular or semi-circular pool shape is considered [248, 413]. Thus, a circular pool of 4 m radius is considered assuming that the rate of burning of LNG is equal to flow rate into the pool. The simulation volume consists of three uniform mesh sizes and mesh independency analysis is performed using four different iterations as illustrated in Figure 5-3.

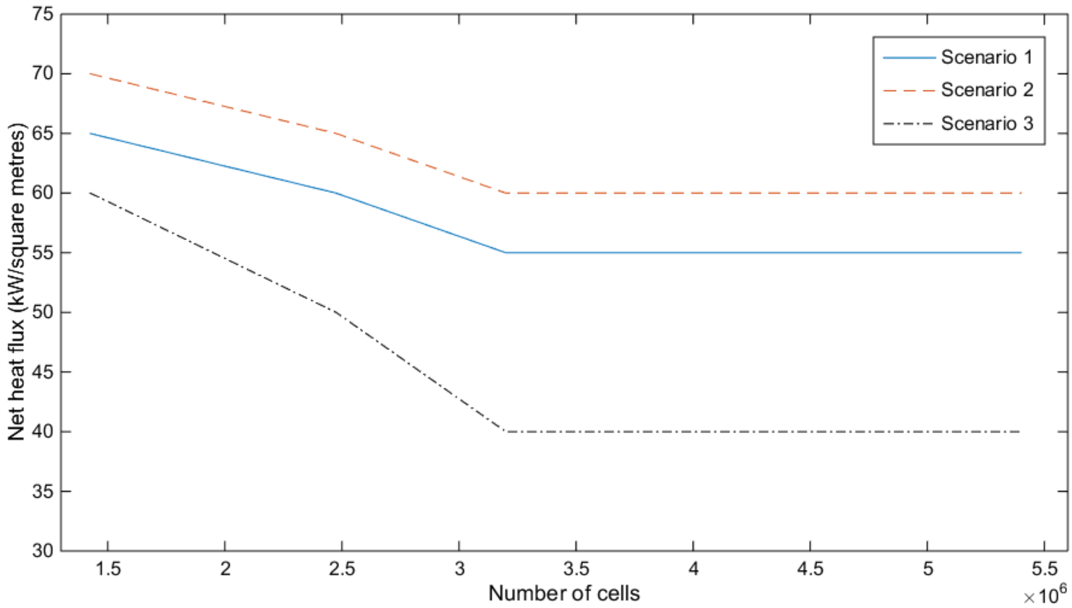

Figure 5-3. Mesh independency analysis

Material properties applied in the modelling are given in Table 5-7. Side and top boundaries of the computational domain are kept open considering ambient atmospheric conditions and the burning rate is taken as 0.177 kg/m^{2}s [414]. It is assumed that the LNG vapour is in the flammability range (5 – 15%) with a quiescent condition. In scenarios 1 and 2, LNG is considered as the fuel involved in the fire with methane considered in scenario 3.

Table 5-7. Material properties used in the PyroSim.

Outer material	**Density (kg/m^3)**	**Specific heat (kJ/(kg·K))**	**Conductivity (W/(m·K))**	**Emissivity**	**Absorption coefficient**
Steel	8050	0.49	16	0.74	5.0E4 1/m

5.3.4. Impacts of the fire accident

The results obtained from the three simulations are compared to obtain the most critical scenario for impact assessment. The impact of the fire is demonstrated based on human impact criteria and assets impact criteria due to thermal loads. In this study, the impacts of combustion products released from the fire are not considered. The consequences of the pool fire on on-board personnel at various distances from the surface of the flame are determined based on the integrated thermal intensity at different locations. Additionally, the human impact thresholds stated by the World Bank [397] against different thermal loads at various locations of the topsides are adopted to identify impacts to personnel. These include 100% lethality in one minute and first degree burns in 10 s when exposed to thermal intensity of 37.5 kW/m^2. Additionally, the probabilities of having first degree burn, second degree burn and death at different locations are calculated. Using Equations 6-9, the yield strength and the modulus of elasticity reductions at various elevated temperatures are calculated to investigate the effects of the fire on the nearby modules.

5.3.5. Risk of the fire accidents

The thermal radiations obtained in each scenario are converted to corresponding risk values. In this case, the fire risk to personnel are estimated around the fire and plotted on the topside of the facility as illustrated in Figure 5-7. The risk values range from 1 at the furthest distance from the fire location to the maximum value of 10 at the flame surface. These risk values represent the overall effects of the probability of first degree burn, second degree burn and death caused by the fire.

5.4. Results and discussion

The results of FDS simulation are discussed based on quantitative values of different factors such as boundary net heat flux, integrated heat flux and adiabatic surface temperature. The impacts of the fire are assessed considering personnel impact and the asset damages criteria. The results of applying the developed methodology for fire impact assessment in FLNG platform on each scenario are discussed in the following sections.

5.4.1. Assets impacts

In order to determine the consequences of the fire on surrounding equipment or structures, integrated intensity at various distances from the flame surface is calculated in each scenario. Using Equations 6-9, the yield strength and the modulus of elasticity reductions of A36 steel at temperatures 720 °C, 700 °C and 620 °C are calculated to investigate the impacts of the fire on the nearby modules.

In scenario 1, it is found that the 37.5 kW/m^2 thermal loads have spread up to 14 m away from the flame surface and within this range, Storage Area 1 and Control Module are located as shown in Figure 5-5. The maximum heat radiation on the nearest module is more than 50 kW/m^2. Therefore, with this thermal load, the steel structures and other materials of the Storage Area 1 and Control Module will incur significant damages.

According to the World Bank [397], 25 kW/m^2 heat intensity is the minimum intensity required for the ignition of wooden materials in prolonged exposure and causes 100% lethality in one minute. This shows that the Control Module and Storage Area 1 would be significantly impacted and they are highly vulnerable to escalating the impact on other units.

Additionally, the impacts of the fire on adjacent assets or equipment can be assessed using temperatures measured on their surfaces. The temperature contour at 538 °C is given in Figure 5-4 and the regions within the black linings have temperatures greater than 538 °C.

Table 5-8. Yield strength and modulus of elasticity reduction of asset due to the fire.

Temperature (T) (°C)	Yield strength at T (MPa)	Reduction of yield strength (%)	Modulus of elasticity at T (GPa)	Reduction of modulus of elasticity (%)
700	55.43	77.83	64.03	67.98
720	49.60	80.16	58	71
620	85	66	92.57	53.7

It is found that the maximum temperature of Storage Area 1 and the Control Module measured at 46.5 s is about 700 °C and the maximum temperature on the protective wall is about 650 °C. At 700 °C, the yield strength and modulus of elasticity of the steel are reduced by 77.83% and 67.98% respectively below that of the normal temperature (20 °C) as shown in Table 5-8. These values are higher than the values recommended by the American Institute for Steel Construction’s Specification for the design, fabrication and erection of steel structures used for buildings construction [401] and ASTM E119 temperature endpoint criteria [415]. Based on these, the pool fire has a significant potential impact on other adjacent assets. As Storage Area 1 contains LNG and the location of the fire is adjacent to the tank, there is a high likelihood of the fire shifting towards the tank. This would certainly have even more damaging and catastrophic consequences due to a domino effect and BLEVE.

According to Reniers and Cozzani [406], the strength of most steel equipment drops rapidly at temperature above 700 K (426.85°C). Moreover, the increasing stress inside the tank weakens the tank wall due to thermal dilatation. These combined effects may lead to the vessel failure and further loss of containment. The threshold radiation value for all equipment failures is considered as 37.5 kW/m^2 [397].

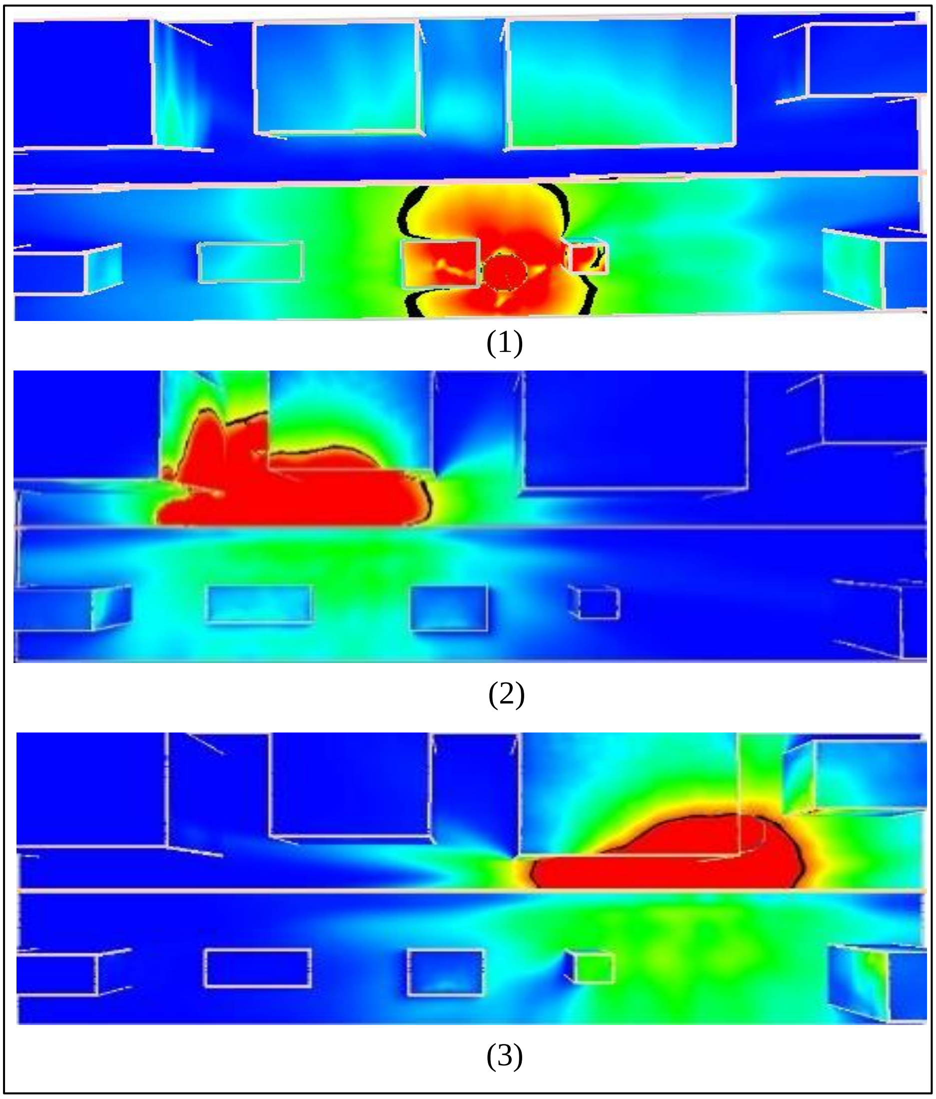

Figure 5-4. Adiabatic surface temperature contour higher than 538 °C in scenarios 1, 2 and 3.

Similarly, the threshold radiation for failure of a tank at atmospheric pressure is 15 kW/m^2 and for the pressurized tank is 50 kW/m^2 in pool fire accident [416]. The maximum temperature of the adjacent units is about 700 °C (973.15 K). Structures of these units may lose strength significantly, as it is known that most common types of construction materials used in process industries lose 40% of their strength at temperatures higher than 670 K (396.85 °C) and lose 80 - 90% strength at temperatures higher than 850 K (576.85 °C) [406]. Therefore, the pool fire has high potential of causing damage in the nearest modules. The maximum temperature and the maximum thermal load generated in this pool fire scenario are above the threshold values, suggesting that the primary pool fire has the capability of causing an evolving scenario of accidents to adjacent units.

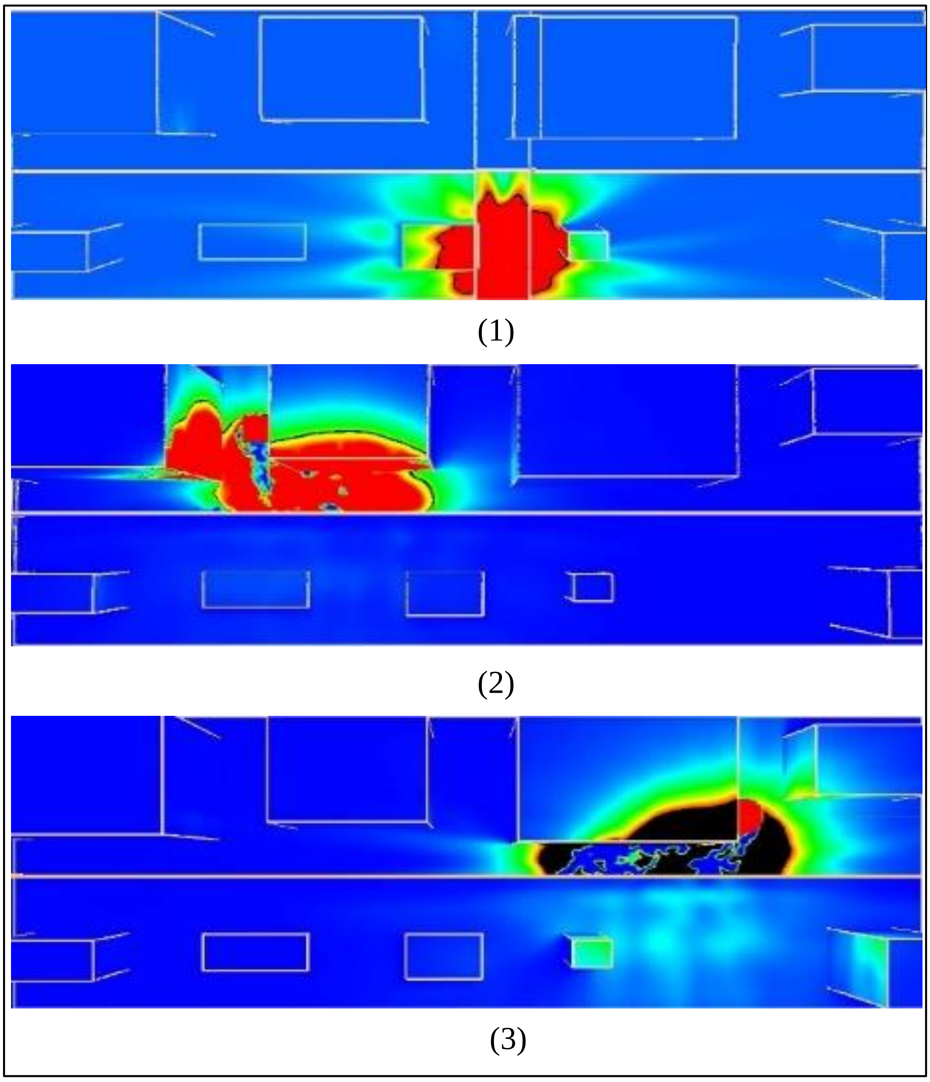

Figure 5-5. Heat flux contours of 37.6 kW/m^2 in scenarios 1, 2 and 3.

In scenario 2, the maximum adiabatic surface temperature on the adjacent assets (PMR Module 2 and MR Module) is 720 °C and the maximum net heat flux is 60 kW/m^2. At this temperature, the yield strength and the modulus of elasticity are reduced by 80.16% and 71% respectively. As the thermal load and surface temperature on the assets are higher than the given threshold values [397, 406, 415]. The fire in this scenario certainly may have severe impacts on the assets. In scenario 3, the maximum thermal load on adjacent assets is 40 kW/m^2 and the maximum surface temperature is 620 °C. The maximum thermal load and the surface temperature are lower than that of scenarios 1 and 2 at the similar simulation period. The heat flux contours of this scenario are given in Figure 5-5 showing it can cause impact on the PMR Module 1 and gas treatment facility.

5.4.2. Personnel impacts

In each scenario, the probabilities of having first degree burn, second degree burn and lethality at various distances of the receptor from the flame surface are estimated. In scenario 1, it is found that the safe distance from the flame surface is about 29 m along open space on the deck. At this location, the probability of injury to personnel is near zero. In scenario 2, these probabilities are calculated as illustrated in Figure 5-6. In this scenario, due to higher output thermal intensity and adiabatic surface temperature, the safe distance from the flame surface is about 37 m along the open space on the deck. In scenario 3, the safe distance to personnel away from the surface of the flame is 19 m along the open space on the deck. Contrary to the other two scenarios, the impacts to on-board personnel would be worse because the fire location is adjacent to the accommodation. However, due to the presence of the protective wall, the impacts are insignificant as illustrated in Figure 5-7 (c).

A damage radius for 100% and 50% fatalities or asset damages in each scenario is calculated and given in Table 5-9. From this comparison, it is evident that the higher heat fluxes are available to a greater area of the adjacent units in scenario 2 as shown in Figure 5-5. In scenario 2, the maximum heat flux attained by adjacent modules is about 60 kW/m^2 which indicates that the equipment has a higher probability of failure in a shorter duration than that in the cases of scenarios 1 and 3. Similarly, the regions with probability of 100% fatality to personnel in one minute (37.5 kW/m^2) are available in a greater area of the topside in comparison to scenarios 1 and 3. This suggests that the scenario 2 may cause more severe consequences to both assets and personnel than other considered scenarios.

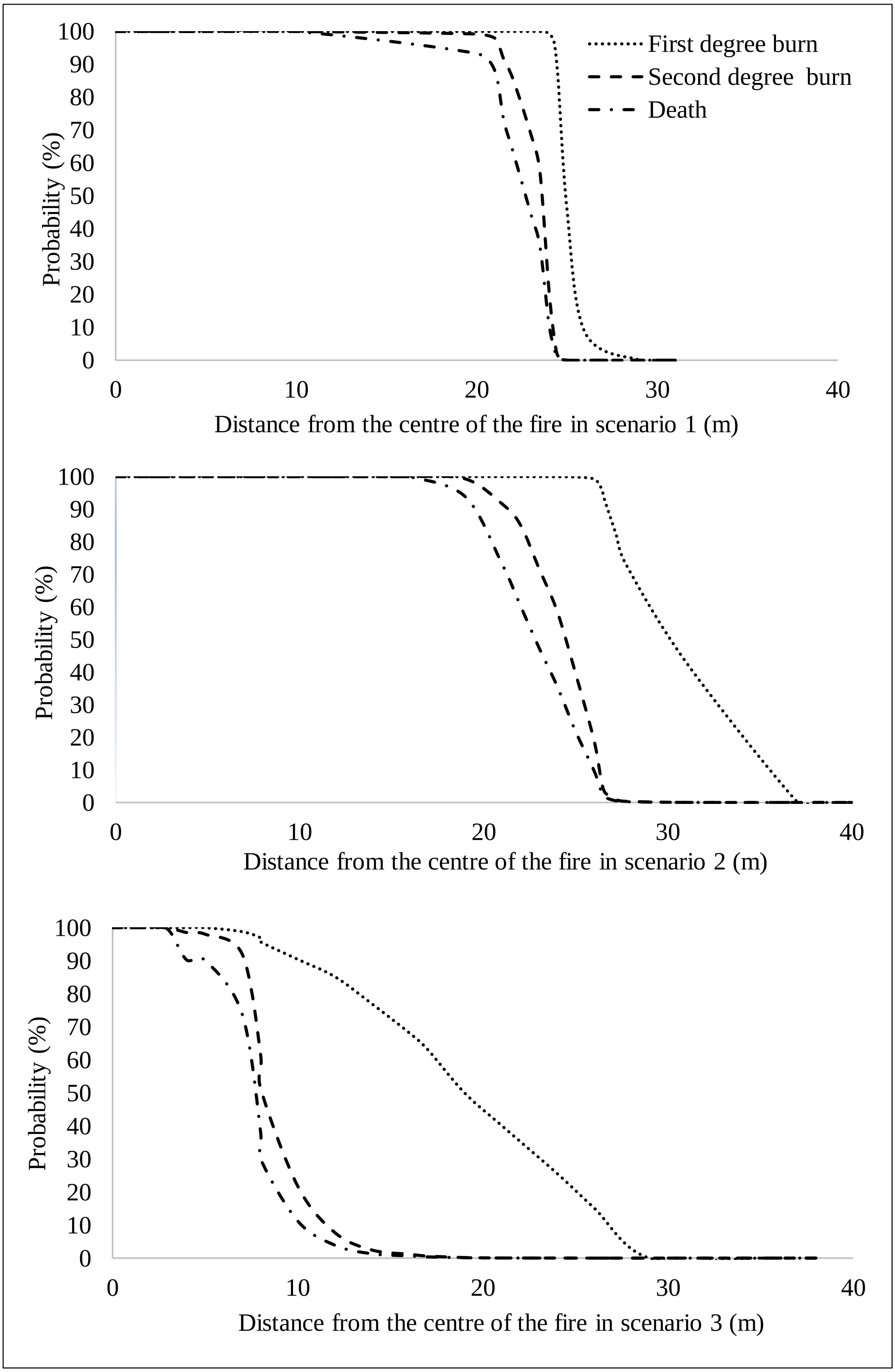

Figure 5-6. Probabilities of human impacts against distance of receptor from the flame surface in the three scenarios.

Table 5-9. Damage calculation results for accident scenarios 1, 2 and 3.

Parameters	**Scenario 1**	**Scenario 2**	**Scenario 3**
Maximum net heat flux on asset surface (kW/m^2)	55	60	40
Maximum adiabatic surface temperature (°C)	700	720	620
Damage radii for 100% fatality or asset damage (m)	5	11	4
Damage radii for 50% fatality or asset damage (m)	9	17	8
Damage radii for 100% second degree burn (m)	7	14	5
Damage radii for 50% second degree burn (m)	11	19	10

5.5. Risk assessment

The thermal radiation contours are converted into corresponding risk contours using risk scores. The range of these values varies from 1 at the furthest distance from the fire location to the maximum value of 10 at the flame surface. These risk scores represent the overall effects of the fire at any location around the fire. This shows that the higher risks are available closer to release or fire location. By comparing risk profiles in the three scenarios as seen in Figure 5-7, it is evident that the higher risk area is available in greater area on the topsides of the facility in scenario 2. Thus, scenario 2 is considered as the most critical scenario in the facility. Contrary to the result of MCAS methodology, scenario 2 has higher impact and risk level than that of scenario 1. This is because in the credibility assessment, the impacts of BLEVE were considered, however, in CFD simulation, the impacts of BLEVE were not included. This investigation initiates the need for simulating the integrated effects of both fire and explosion events using CFD in FLNG accident modelling and impact assessment in future.

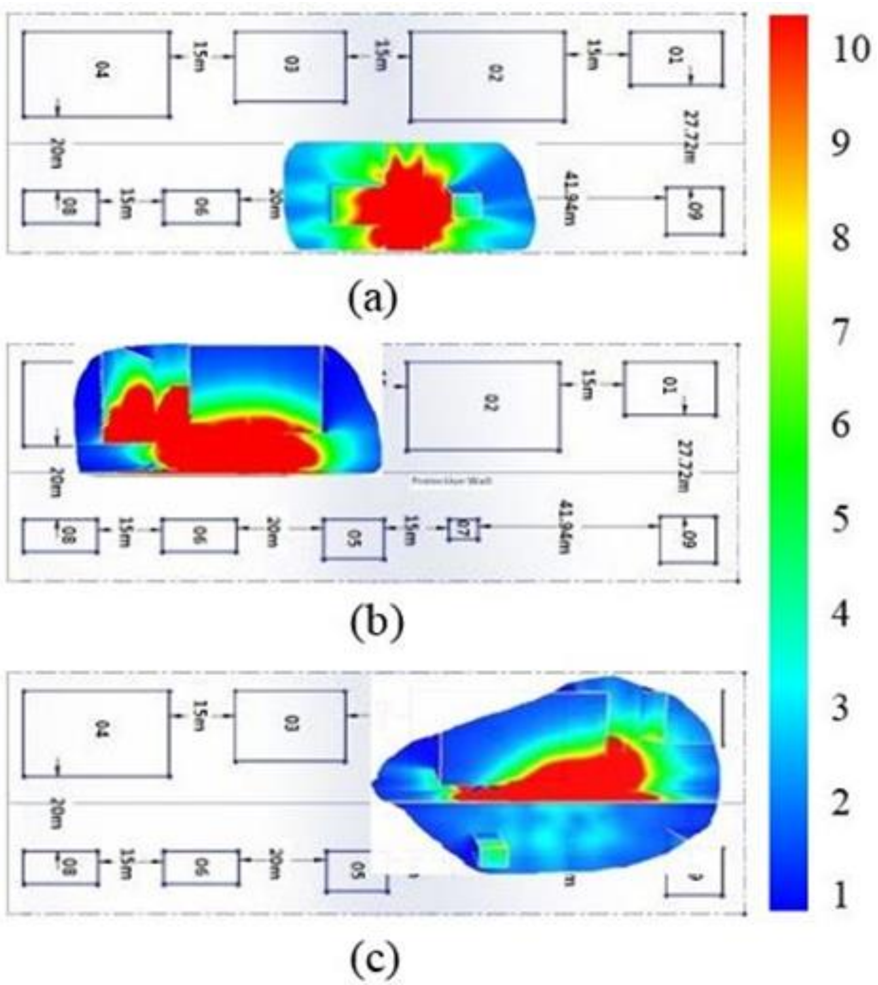

Figure 5-7. Comparison of fire risk to personnel in (a) scenario 1, (b) scenario 2 and (c) scenario 3.

5.6. Conclusion

In this study, a novel methodology is developed for modelling the impact of fire event in FLNG processing facilities. Using the methodology, 32 plausible fire accident scenarios on the topsides of the facility are selected and the three most credible accident scenarios are identified. The LNG spill due to leakage of outlet valves or overfilling of tank thereby forming an LNG pool with immediate ignition is found to be the most credible accident scenario on the facility under the stated conditions. The three most credible fire scenarios are separately modelled and simulated using FDS codes. The output results obtained from the FDS simulations confirmed that the net heat fluxes and the adiabatic surface temperatures on adjacent assets are higher than the threshold values. These scenarios have a high potential to cause evolving fire scenarios in the facility because in all scenarios, the steel structures or equipment would fail to support the designed loads and would pose a greater threat of escalating effects. The escalating effects due to structural or equipment failure of adjacent assets may cause catastrophic consequences. The comparisons of fire impacts, indicate that the scenario in the MR Module of the liquefaction process has more severe consequences on both asset and personnel in comparison to scenarios 1 and 3. The impact and consequences to humans would be fatal or of life threatening injuries if they were exposed to those temperatures and heat radiation within the radius of 37 m from the surface of the flame as in scenario 2. The developed methodology can be further applied for safety measures design using fire resistance or fire suppression systems in order to mitigate or avoid the potential impacts of fire events.

Chapter 6

Modelling an Integrated Impact of Fire, Explosion and Combustion Products during Transitional Events in a Complex Processing Facility

Abstract

In a complex processing facility, there is likelihood of occurrence of cascading scenarios, i.e. hydrocarbon release, fire, explosion and dispersion of combustion products. The consequence of such scenarios, when combined, can be more severe than their individual impact. Hence, actual impact can be only represented by integration of above mentioned events. A novel methodology is proposed to model an evolving accident scenario during an incidental release of LNG in a complex processing facility. The methodology is applied to a case study considering transitional scenarios namely spill, pool formation and evaporation of LNG, dispersion of natural gas, and the consequent fire, explosion and dispersion of combustion products using Computational Fluid Dynamics (CFD). Probit functions are employed to analyze individual impacts and a ranking method is used to combine various impacts to identify risk during the transitional events. The results confirmed that in a large and complex facility, an LNG fire can transit to a vapor cloud explosion if the necessary conditions are met, i.e. the flammable range, ignition source with enough energy and congestion/confinement level. Therefore, the integrated consequences are more severe than those associated with the individual ones, and need to be properly assessed. This study would provide an insight for an effective analysis of potential consequences of an LNG spill in any LNG processing facility and it can be useful for the safety measured design of process facilities.

Keywords: LNG spill, accident transition, integrated consequence, CFD

6.1. Introduction

In a complex processing facility such as a floating liquefied natural gas (FLNG), an incidental release of LNG may not simply lead to an event with only its individual impact. There is likelihood of escalating a minor event into more damaging events. For instance, an accidental release of LNG in a production facility has the potential to pose several hazards such as fire, explosion, brittle fracture, asphyxiation and freeze burn/frostbite. A leakage of LNG may be a single minor event itself. However, due to instantaneous vaporisation, it is likely to cause several events such as a fireball, flash fire, Vapour Cloud Explosion (VCE), and pool fire when the vapour is ignited. Escalation of the mentioned events to a storage facility, may lead to Boiling Liquid Expanding Vapour Explosion (BLEVE). The entire sequence of events and their interactions during an LNG spill event in an FLNG processing facility is illustrated in Figure 6-1.

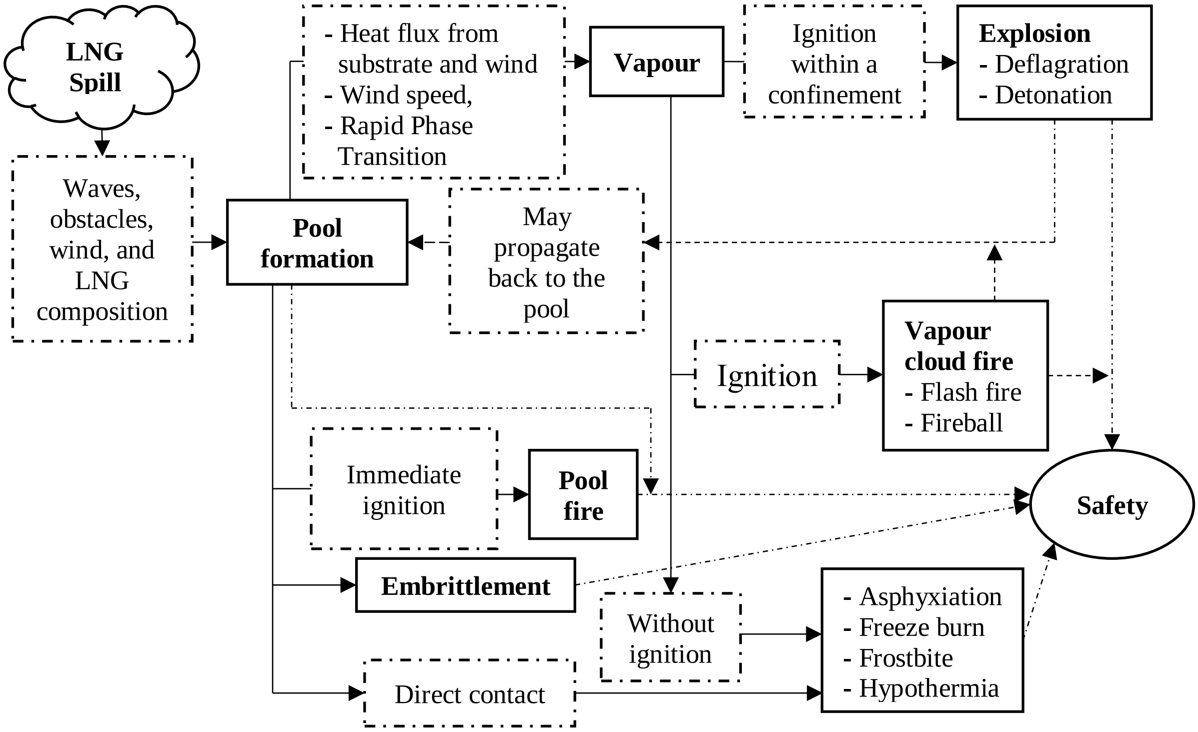

Figure 6-1. LNG spill events (adapted from Ikealumba and Wu [417] with some modifications).

Due to the potential of having several events during an unintended LNG spill, the US Government Accountability Office (GAO) commissioned a study and recommended to improve the state of knowledge surrounding the potential for cascading damage to LNG vessels in the case of an incidental release of LNG [239]. The study of cascading damage issues has proven difficult primarily because these events require the analysis of the interaction of a series of complex physical phenomena such as LNG flow, heat transfer, fracture and damage. Petti *et al.* [249] summarized the outcomes of the studies on cascading damage [48, 418, 419] which explored the cryogenic and fire thermal damage to an LNG ship during a large LNG cargo tank breach.

In these studies [48, 418, 419], impacts (pressure wave, shrapnel or projectile) from the explosion are not considered in the cascading damage analysis. Examples of evolving accident scenarios are reported in [300, 420]. The Piper Alpha tragedy in 1988 caused 165 deaths due to an explosion after the release of flammable material. In the accident, leakage of gas occurred, and the presence of an ignition source caused multiple events such as a fireball and jet fire, followed by VCEs. The sequence of events led to the total loss of the platform [11]. In 2004, an LNG accident occurred in the Skikda LNG plant in Algeria resulting in 27 casualties, 56 injuries and $900 million loss. During this multiple explosions occurred due to excessive pressure in an adjacent boiler [300]. The BP's Texas City refinery explosion in 2005 caused 15 deaths and 180 injuries due to hydrocarbon release and subsequent fire and explosion [421]. The release resulted in a VCE followed by a pool fire [422]. In 2010, the Macondo accident in the Gulf of Mexico occurred with a series of events such as blowout, dispersion of released hydrocarbons, explosion and fire [423]. The flame propagating from the explosion reached the flammable vapour dispersed over the platform and led to the fire at the source of release at the drilling floor. Major accidents that occurred in process facilities are well explained in [52, 336, 424]. These accidents are mainly associated with fires, explosions and toxic product release. Most past studies regarding fire and explosion accidents were limited to individual fires or explosions or combustion products modelling and did not address evolving accident scenarios [23, 25, 49, 50]. For instance, Dadashzadeh *et al.* [50] modelled the dispersion of flammable gas integrated with explosion consequences of the BP Deepwater Horizon explosion using a Flame Acceleration Simulator (FLACS). Smoke and heat radiation released from the fire also affect human health and offshore structures; however, this impact was not addressed in the consequence analysis. Dadashzadeh *et al.* [23] proposed a methodology for toxicity risk assessment during an LNG fire and revealed that high risks are found at the process facility due to higher concentrations of combustion products and longer exposure time. However, the direct consequence of fire was not considered. Baalisampang *et al.* [51] and Baalisampang *et al.* [309] modelled the impact of a fire in a typical FLNG processing facility. Other potential events, their interactions, and consequences were not included by Baalisampang et al. [425]. Kim and Salvesen [49] conducted a study on LNG vapour release, which was addressed as a possible VCE. However, a potential fire scenario was not considered. Another study by Koo *et al.* [374] focused on pool fire modelling only and no consideration was given to a VCE or other possible interactions such as a jet fire. But in most cases, fire, explosion and combustion product release occur one after another or simultaneously resulting in integrated consequences [241, 358].

Reviews of past accidents [50, 52, 421] and models [49, 52, 374, 426] demonstrate a need to evaluate the entire accident sequence to mitigate the impact, to develop appropriate response methods and to prevent accidents by designing safety measures in the system. Combination of various accidental events is important as one event may lead to another and increases the overall consequences. To model entire impacts of a potential accident in a complex processing facility, it is essential to consider transitional event scenarios because in such modelling, entire causes and effects of a series of events are considered. In comparison to onshore processing facilities, offshore facilities are deemed more vulnerable to transitional events due to limited topside space and harsh environmental conditions [236]. Some offshore accidents involving transitional events are given in Table 6-1.

Table 6-1. Offshore fire and explosion accidents associated with multiple events

Accident name, year and geographical region	**Event sequence**	**Consequences**	**References**
Piper Alpha, 1988, Europe North Sea	Release → Explosion → Fire	165 fatalities, total loss	[11]
High Island Pipeline, 1989, US GOM	Collision → Release → Explosion → Fire	11 fatalities, 4 injuries and significant damage	[365]
Enchova Central, 1984, America South East	Blowout → Fire → Explosion	42 Fatalities, 19 injuries and significant damages	[365]
Lake Maracaibo, 1993, America South East	Explosion → Fire	11 fatalities, significant damage	[365]
Ubit, 1995, Africa West	Explosion → Fire	10 fatalities, 23 injuries and severe damage	[365]
Petrobras P-36, 2001, America South East	Explosion → Fire → Capsizing	11 fatalities, total loss	[365]
Bombay High North, 2005, Asia South	Collision → Release → Fire	12 fatalities, severe damage to the jacket	[365]
Deepwater Horizon, 2010, GOM	Blowout → Release → Fire → Explosion	11 people died, 17 injuries and total loss	[423]
Black Elk, 2012, GOM	Release → Fire → Explosion	3 people died, pollutant spill	[427]
SOKAR platform, 2014, Caspian Sea	Explosion → Fire	12 people fell into the sea	[428]
Abkatun Alfa platform, 2015, GOM	Explosion → Fire	7 people died, 45 injuries	[429]

In fire and explosion accidents, a combined impact assessment is assumed to provide a more accurate consequence than individual one. In fire and explosion accidents, a damage potential (radius) can be increased if the impact of combustion products is considered [23]. During fire and explosion accidents, depending upon the types of burning materials and their combustion products, people are exposed to adverse health effects. For an integrated impact study, Khan and Amyotte [53] proposed a methodology that incorporated fire, explosion and toxic release damage indices to evaluate the inherent safety of a facility based on inherent safety guidelines. Dadashzadeh *et al.* [54] proposed a new methodology for modelling an integrated consequence of fire and explosion using the Fire Dynamics Simulator (FDS) and FLACS and concluded that the risk of combined consequences is higher than each individual risk. But potential risk from combustion products during fire and/or explosion was not considered in the study. Niazi et al. [430] proposed an integrated consequence modelling approach for fire and combustion products using risk based and grid-based approaches and claimed that the risk posed by thermal radiation is confined only to the lower deck. But the risk of exposure to combustion products was present in a larger area than that of the radiation, due to the influence of wind. Unlike previous studies [53, 54, 430], the current study proposes a risk-based approach to model an integrated impact of fire, explosion and combustion products during an accidental release of LNG in a typical FLNG processing facility.

6.2. Methodology

This study proposes a methodology that models an integrated impact of evolving accident scenarios such as release, pool fire, explosion events and dispersion of combustion products as illustrated in Figure 6-2. Currently, several Quantitative Risk Assessment (QRA) softwares tools such as IMESAFR [431], Riskcurves [432], EFFECTS [433], Riskan [434], HAMS-GPS [435] and Phast and Safeti [436] are available for accident modelling. They are simpler and faster than most CFD tools. A majority of QRA software tools lacks the capability of considering complex effects of geometry and equipment in the simulation and cannot model evolving accident scenarios. But this study considers the effect of complex geometry and/or equipment and models cascading events and their impacts using the following five steps.

In step 1, LNG release scenario, pool formation, vaporisation and dispersion of LNG vapour are modelled using FLACS. These phenomena are simulated with careful consideration of plausible scenarios.

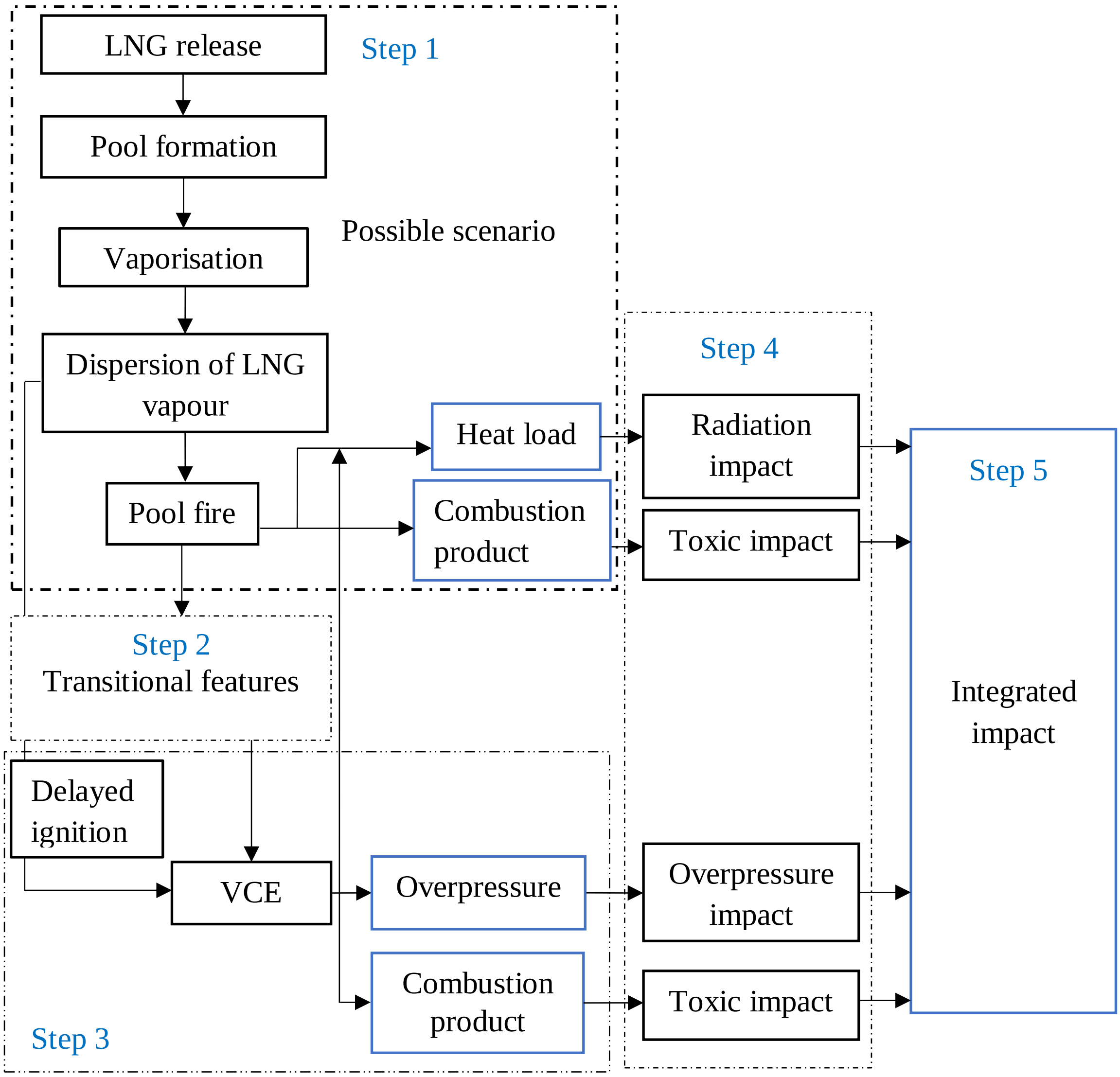

Figure 6-2. Proposed methodology for modelling an integrated impact of transitional events to human during an LNG spill.

In step 2, the potential transitional phenomena are considered by attending to a series of events such as dispersion of LNG vapour, pool fire and VCE. The phenomenological changes to spilled LNG and vaporisation due to a culmination of atmospheric effects and thermal radiation are considered for assessing the occurrence of potential cascading events. The thermal load obtained from the pool fire is used as the source of ignition for the VCE. For transitional events to occur, some minimum conditions need to be fulfilled. For instance, a dispersion event can transit to pool fire only if the flammability condition is met. Similarly, a VCE occurs when pertinent conditions such as confinement, turbulence, ignition source, and flammable gas cloud are present [301, 437]. These pertinent conditions are considered as stimuli for the transitions (events) [438]. During a release, with the vaporisation and dispersion of LNG in air, only a vapour concentration in the range of 5-15 vol.% will sustain the propagation of a flame upon ignition. The concentration of the vapour above the upper explosion limit may act as feed gas to the fire. However, if the dispersed vapours accumulate in nearby semi-confined or confined areas, the fire may transform to a VCE upon ignition. This may increase the severity of consequence in total. If the flammable gas release is not ignited immediately, a vapor plume will form which will drift and disperse by the ambient winds and/or natural ventilation. If the vapour is ignited, but does not explode, it will result in a flash fire, in which the gas cloud within the flammable range burns very rapidly. If the vapour is not isolated during this time, the flash fire may burn to yield a jet fire at the source of the release, under the condition that the concentration range is appropriate, and the leak is present.

In step 3, the heat released from the pool fire is modelled as the potential ignition source to ignite the flammable gas accumulated at a position away from the pool fire location such that the fire did not consume the rich vapour cloud from this location. It was assumed that this location did not get direct fire flame and the presence of high thermal radiation from the fire resulted in an autoignition of the vapour or influenced other ignition sources to ignite. During a release of a flammable gas, if the ignition is delayed by 5-10 min, a VCE may be the outcome [26, 439]. For ignition to take place, the vapour cloud must be within the flammable range, while at the same time a source able to supply the required energy must be available [26]. To model a pool fire transiting to a VCE, thermal radiation and other parameters such as temperature and pressure development are extracted from the previous step. There are various models available for gas explosion modelling, like empirical, phenomenological and CFD [440]. According to Tam and Lee [441], CFD codes are inherently more flexible than both empirical and phenomenological models and are applicable to all fields. Some commonly used CFD models for explosion simulations are EXSIM, FLACS and AutoReaGas [440]. FLACS developed by the Global Explosion Consultants (GexCon AS) has been used widely for the modelling of gas dispersion and explosion in onshore or offshore facilities [259]. In this study, FLACS is used to model the fire and explosion scenarios.

In step 4, the consequences of fire, explosion and/or combustion product release are analysed individually using probit functions. The heat load obtained from the fire is used to assess the fire impact to assets and people. The probability of human impacts from the heat radiation is calculated by Eq. (6-2), considering the probit model given in Eq. (6-1).

Probit function $(Pr) = c_1 + c_2 \ln D$, (6-1)

The probability of injury or death $(P) = F_k \frac{1}{2}\left[1 + erf\left(\frac{Pr - 5}{\sqrt{2}}\right)\right]$, (6-2) where D is the thermal dose $(\frac{kW}{m^2})^{\frac{4}{3}}s$, c_1 and c_2 are probit coefficients, F_k is a clothes correction factor, and *erf* is the error function. The thermal dose is obtained from the post processing file using inbuilt utilities in FLACS.

Sudden large changes in pressure due to an explosion can lead to dramatic and possibly fatal damage to vital human organs such as lungs and ears. The impact of explosion is assessed based on the calculation of the probability (P) of injury or death employing Eqs. (6-3)-(6-8).

Probit function (Pr) = $c_1 + c_2 \ln S$, (6-3)

The probability of injury or death (P) $= \frac{1}{2}\left[1 + erf\left(\frac{Pr-5}{\sqrt{2}}\right)\right]$, (6-4)

where variable S is defined according to the type of the effect calculated by S = $(\frac{4.2}{\bar{P}} + \frac{1.3}{\bar{\iota}})$,

where $\bar{\iota}$ is the scaled impulse $\left(Pa^{\frac{1}{2}}.s.kg^{-\frac{1}{3}}\right)$, $\bar{P}$ is scaled pressure (-) and c_1 and c_2 are probit coefficients [26]. Explosion effects on humans are usually categorised as:

1. Direct or primary effects

   The overpressure from the explosion can cause injury to sensitive human organs, or death.

2. Indirect effects

   The indirect effects are sub-divided into two categories

   a. Secondary effects refer to injuries or death caused by fragments or debris thrown by explosion's blast,

   b. Tertiary effects that refer to injuries or death caused by whole-body displacement and collision with stationary objects or structures, because of the explosion's blast waves.

The probabilities of impact to lung, eardrum rupture, head impact and whole-body displacement impact are calculated using Eq. (6-4). However, the *Pr* are different. In this study, the following probit functions are used for each type of impact [26].

For lung damage, $Pr = 5 - 5.74 \ln S$ (6-5)

For eardrum damage, $Pr = -12.6 + 1.524 \ln P_s$ (6-6)

For head impact, $Pr = 5 - 8.49 \ln S$ (6-7)

For whole-body displacement, $Pr = 5 - 2.44 \ln S$ (6-8)

where P_s is overpressure (Pa). According to Clancey [442] cited in Crowl and Louvar [14] 1-99% fatalities can occur when exposed to over 2 bar.

Toxicity of combustion products accounts for a major cause of death and injury from unwanted fires [443]. The main combustion products are divided into two types: asphyxiant gases, which prevent oxygen uptake by cells, leading to loss of consciousness and death; irritant gases which cause immediate incapacitation affecting eyes and upper respiratory tract long-term damage in the lung [444]. Because of these harmful effects, they can seriously jeopardise evacuation. During an LNG fire or VCE, carbon monoxide (CO) and nitrogen dioxide (NO_2) are the main toxic combustion products [23].

In the step 5, the integrated impact of fire, explosion and combustion product release is estimated. For integration of fire and VCE effects a grid-based approach is used such that consequence severity can be mapped as an index. To estimate risk of each event, a risk-based approach was further adopted using a severity index and probability of each effect. The severity index for each type of effect (S_i) is estimated using expert judgment. The effects are ranked based on their severity of damages (Table 6-2) and experts' judgment on a scale of 1–10.

Table 6-2. Severity scores for human effects caused by fire and explosion [54]

	Fire			**Explosion**			
Effects	First degree burn	Second degree burn	Death	Lung damage	Eardrum rupture (injury)	Head impact (death)	Whole body displacement (death)
Score (S)	2	5	10	10	5	10	10

The severity index for each effect at any location of the plant is calculated as follows:

$$Risk_i = S_i \times P_{i,} \quad (6\text{-}9)$$

Where, $Risk_i$ denotes the severity index for each effect and i denotes the effects (first degree injury, second degree injury and death for fire; lung damage, eardrum rupture, head impact and whole-body displacement for explosion). At each grid point, the maximum severity index among the various effects of each accident is considered using Eqs. (6-10) and (6-11) for a fire and explosion respectively.

$$Risk_f = \text{maximum}\ [Risk_{\textit{First degree burn}}, Risk_{\textit{Second degree burn}}, Risk_{\textit{Death}}] \quad (6\text{-}10)$$

$$Risk_e = \text{maximum}\ [Risk_{\textit{Lung}}, Risk_{\textit{Eardrum}\ \text{damage}}, Risk_{\textit{Head impact}}, Risk_{\textit{Whole body displacement}}] \quad (6\text{-}11)$$

The total risk of fire and VCE ($Risk_{fe}$) at any location is estimated using Eq. (6-12),

$$Risk_{fe} = Risk_f + Risk_e \quad (6\text{-}12)$$

Using the $Risk_{fe}$ at any location of the layout, risk contour can be obtained considering cumulative effects of a fire and VCE.

The toxicity risk assessment is carried out according to the methodology proposed by Dadashzadeh *et al.* [23]. A hazard index (HI) was estimated at each grid point of the layout using Eq. (6-13) [445].

$$HI = \frac{Estimated\ concentration\ (mg/m^3)}{Reference\ toxic\ value\ (mg/m^3)} \quad (6\text{-}13)$$

For toxic risk estimation of each contaminant of the combustion product, Eq. (6-13) can be written as in Eq. (6-14).

$$\mathrm{Risk}_{combustion\ product} = \frac{Exposure\ concentration}{TLV-STEL} \quad (6\text{-}14)$$

Where TLV-STEL is the Threshold limit value - Short Term Exposure Limit (mg/m^3). By adding the hazard quotients (hazard indices) for the individual emission toxicants, the hazard quotient of all toxicants is obtained as shown in Eq. (6-15). A risk of a health effect is assumed to exist at those exposure locations where the hazard index exceeds 1.

$$Risk_{Total\ combustion\ product} = Risk_{CO} + Risk_{NO_2} \quad (6\text{-}15)$$

Finally, the integrated risk at any location of the facility is estimated by investigating the Risk_{fe} and the $\mathrm{Risk}_{combustion\ products}$ under any considered scenarios.

6.3. Application of the integrated methodology: A case study

The proposed methodology is applied to a typical layout consisting of several process equipment as shown in Figure 6-3. Leak, vaporisation and dispersion are strongly dependent on the operating parameters and may need to consider prevalent operating conditions. In this case study, prevalent operating conditions are considered based on FLACS user's manual [261]. In this scenario, 10 kg/s of LNG is released at an LNG processing plant. According to Woodward [341] the appropriate wind speed for flammable cloud dispersion is usually close to 2 to 4 m/s and thus, the wind speed is taken as 3 m/s with an ambient temperature of 20°C. A pool of LNG is formed at the release location and vaporization occurs due to the ambient conditions. The vaporized LNG is then dispersed by the wind and a fuel vapour cloud is formed in the process area. At 125 s, an ignition occurs in the process area which leads to a pool fire. After 55 s the fire transits to a VCE in the congested and confined portion of the facility. This time is chosen based on the presence of the maximum thermal radiation in the layout. The heat load released due to the fire enhances the LNG vaporization over the LNG pool and causes a VCE. A transitional scenario is developed considering the inherent characteristics of the LNG spill and various potential events (such as pool formation, spreading, vaporization, and vapour dispersion) are modelled.

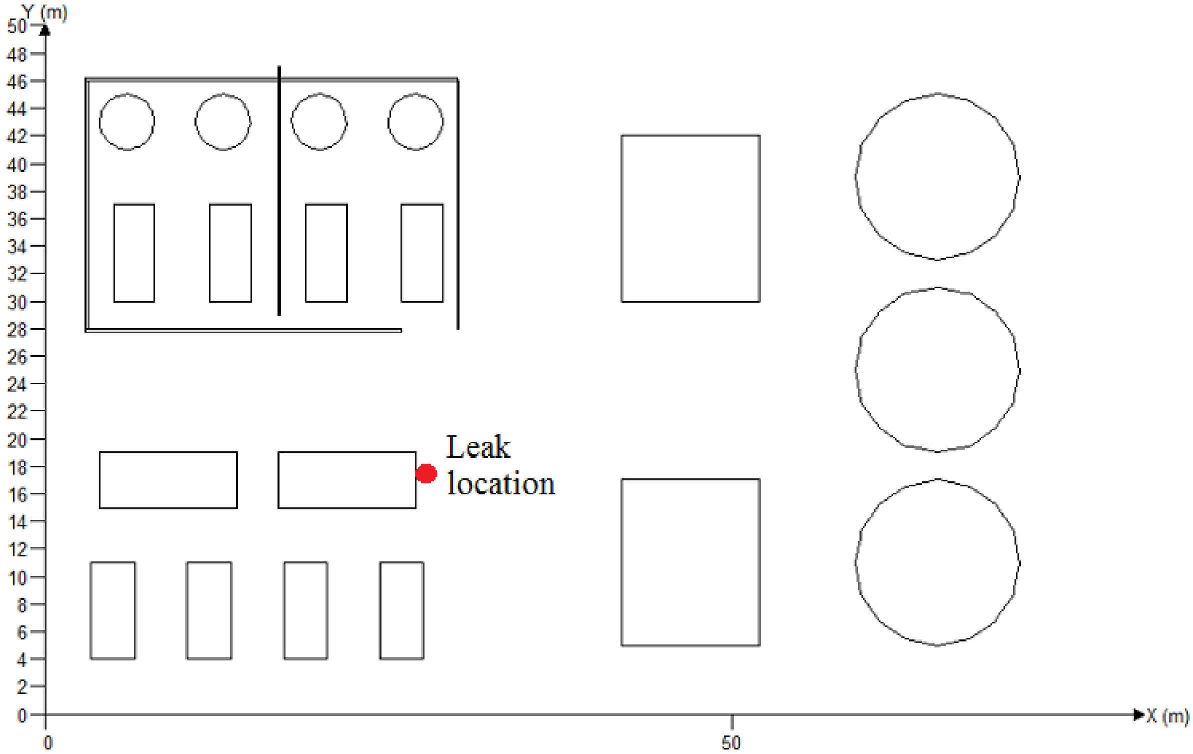

Figure 6-3. A layout chosen for the transitional events modelling

6.3.1. Release, pool formation, vaporisation and dispersion modelling

In this scenario, an instantaneous release of LNG is considered which led to a pool formation and formed a flammable vapour plume upon vaporisation. A pool fire is considered with a delayed ignition. The entire layout 85 m × 55 m × 20 m is considered for simulation with a grid resolution of 0.4 m for the x and y directions and 0.3 m in the z direction. A sensitivity analysis was performed using volumetric concentration to select the grid size for a solution independent of the mesh size. Around the leak location, the grid resolution was adjusted to 0.2 m while at the locations far from the pool area, grids were stretched according to grid refinement guideline given in GexCon AS [261]. The LNG was assumed to be composed of 85% methane, 10% ethane and 5% propane. According to Pitblado *et al.* [254] the maximum credible puncture hole is 250 mm. Thus, a point leak is considered from a 0.05 m^2 hole for 120 s forming a pool. A dynamic pool model (PM3) is chosen which means that the pool spreads with non-uniform pool temperature due to the influence of heat and mass transfer in each control volume [261]. A constant evaporation rate of 0.14 kg/(m^2s) is considered based on the OPG [413]. The considered leak parameters are given in Table 6-3.

Table 6-3. Leak parameters considered in the release scenario

Leak type	Jet
Leak position	(26.5, 20, 1.2) m
Leak direction	+X
Start time	5 s
Duration	120 s
Outlet	
g. Area	0.05 m^2
h. Mass flow rate	10 kg/s
i. Relative turbulence intensity	0.02 (Low)
j. Turbulence length scale	0.025 m
k. Temperature	-160°C

The initial and boundary conditions assigned for the simulation are provided in Table 6-4 and Table 6-5 respectively. The Euler boundary condition is a zero pressure condition and demands significant distance in all directions [261].

Table 6-4. Initial conditions used

Parameters	**Values**
Characteristic velocity	0.1 m/s
Relative turbulence intensity	0.1
Turbulence length scale	0.01 m
Temperature	20 °C
Ambient pressure	100 kPa
Ground roughness	0.001 m
Reference height	2 m
Pasquill stability class	F

Table 6-5. Boundary conditions

Name	**Type**
XLO	Wind
XHI	Euler
YLO	Wind
YHI	Euler
ZLO	Euler
ZHI	Euler

All parameters required for post processing are given in Table 6-6.

Table 6-6. A list of simulated parameters

Output parameters	**Unit**
Pressure (P)	barg
Maximum pressure (PMAX)	barg
Velocity vector (VVEC)	m/s
Combustion product mass fraction (PROD)	-
Temperature (T)	K
Mass fraction of carbon monoxide (CO)	-
Radiative heat flux (QRAD)	kW/m^2
Total heat flux (Q)	kW/m^2
Mass fraction of soot (SOOT)	-
Heat dose (QDOSE)	$((kW/m^2)$^(4/3)s)
Mass fraction of Nitrogen Dioxide (NO_2)	-
Probability of death (PDEATH)	-
Toxic probit (PROBIT)	-
Toxic concentration (TCONS)	mg/m^3
Toxic dose (TDOSE)	mg/m^3.minute

The vaporised fuel concentrations in the layout are monitored during the dispersion as shown in Figures 6-4 and 6-5. The presence of flammable concentrations (0.05 - 0.15) indicates that the fuel has the potential to be ignited in several areas of the layout. This would likely contribute to the occurrence of transitional events or evolving accident scenarios.

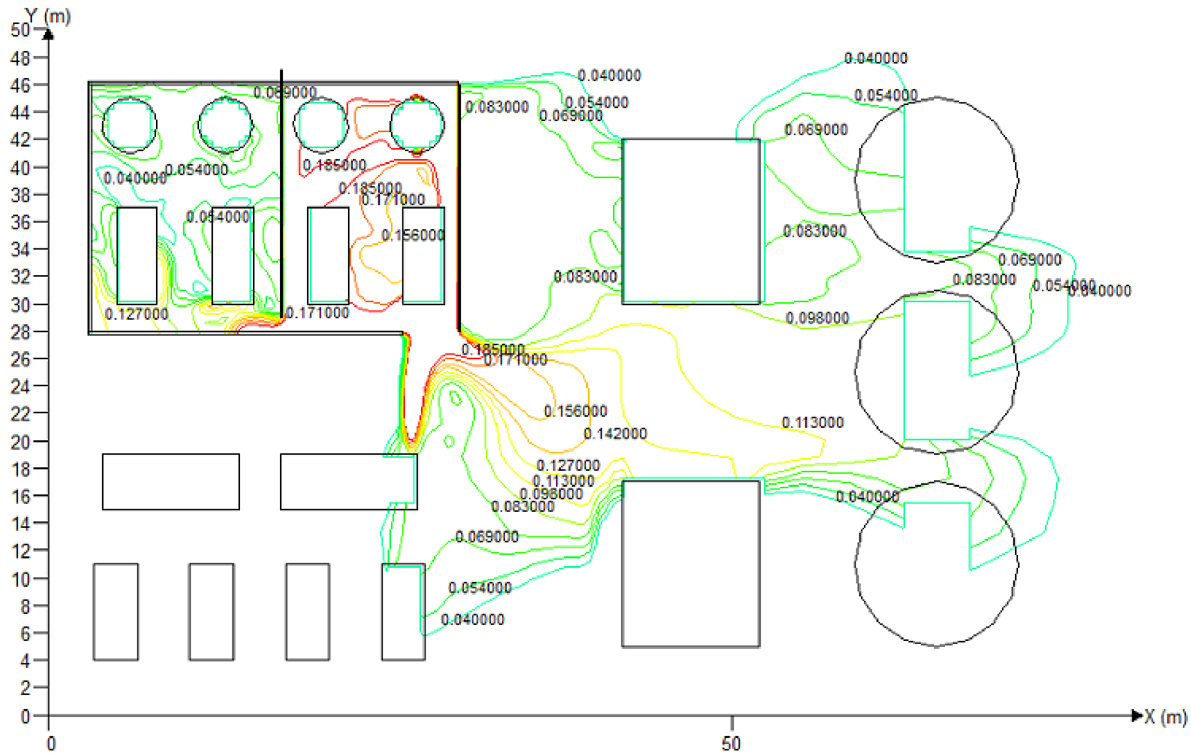

Figure 6-4. Dispersion of vaporised LNG over the layout (m^3/m^3) at time 125 s

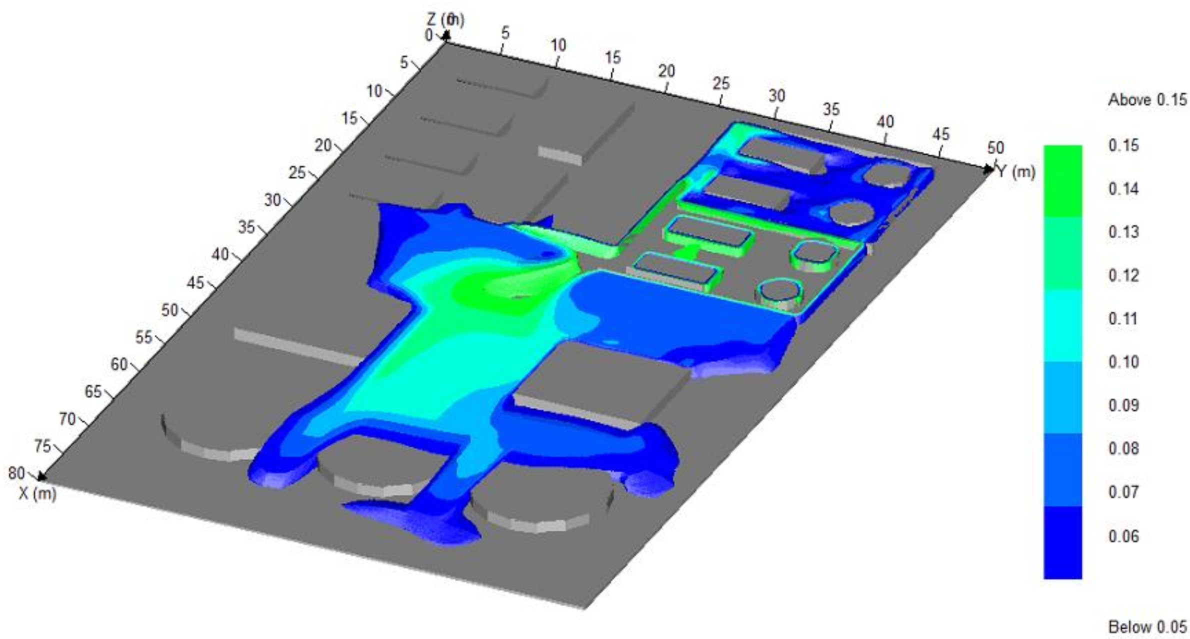

Figure 6-5. 3D dispersion of fuel in the layout (m^3/m^3) at 125 s which shows the maximum volume of gas cloud.

6.3.2. Assessing the possibility of transitional features

A VCE is considered as the final event and to identify transitional features, fire modelling is considered. Based on the dispersion characteristics of the LNG vapour, a pool fire is modelled with a delayed ignition 125 s using the FLACS fire model as demonstrated in Figure 6-6. In the fire simulation, the Discrete Transfer Method (DTM) model is used because this is the most accurate radiation model [261]. Emissivity of 0.85 is used because it is applicable to most steel surfaces. To provide numerical stability, radiation start ramp is considered to be 1 [261]. The Eddy Dissipation Concept (EDC) is chosen as the combustion model. The Formation Oxidation model is chosen as the soot model. For typical hydrocarbons, the soot yield is in the order of 1% [261]. Radiation, smoke and engulfment are the main hazards of a pool fire [446]. The possibility of ignition of the accumulated LNG vapour due to the thermal radiation release from the fire needs to be assessed for transitioning to a VCE.

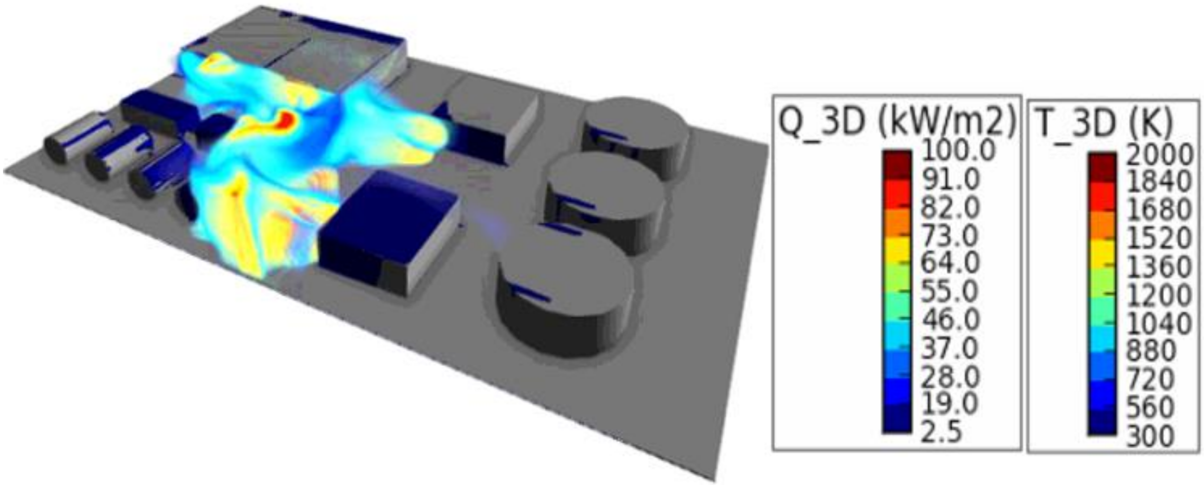

Figure 6-6. 3D pool fire model at 125 s

The main purpose of the transitional event modelling is to analyse if the fire or dispersed vapour can cause a VCE or flash fire in the presence of an existing fire. The most likely location of a VCE can be identified based on the presence of a flammable concentration of LNG vapour, confinement/equipment congestion and ignition source. An autoignition can be a source of ignition of the vapour or heated objects due to the thermal radiation from the fire [447, 448]. According to the fuel concentration and its developed pressure during LNG vapour dispersion, a transition of the pool fire to a VCE is modelled. The transition from fire to VCE is considered after 55 s of the start of the fire, that is at 180 s. The small pressure developed during LNG vapour dispersion is demonstrated in Figure 6-7.

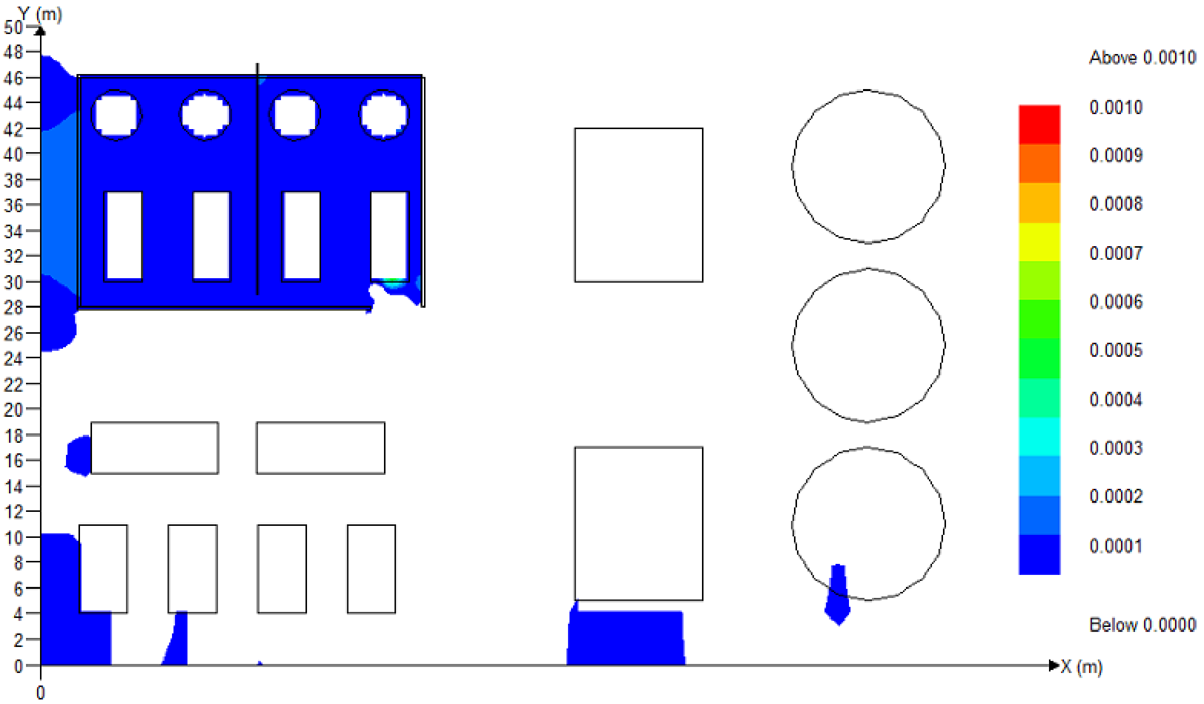

Figure 6-7. Pressure developed in in the layout during dispersion of the fuel (barg)

6.3.3. Toxic potency assessment of combustion products

During LNG (mainly methane) fire, CO, Carbon dioxide, NO_2, unburnt methane and water are produced as combustion products depending on complete or incomplete combustion reaction. In this study, only CO and NO_2 are considered for toxic potency assessment owing to their high toxicity [23]. The different symptoms and health effects of CO and NO_2 are found in Purser et al. [449] and the National Research Council [445] respectively.

6.3.4. Integration of impact analysis

In this current study, an integrated impact analysis is conducted according to the step 5 of the methodology. The risks severity of combustion products was not directly normalised with those of thermal radiation and overpressure. However, an integrated impact analysis is conducted by investigating the risk contours of fire, VCE and combustion products. Similar to Dadashzadeh *et al.* [54], an integrated risk contour is used for assessing the impact of transitional accident scenarios in the facility.

6.4. Results and discussion

6.4.1. Results for transition modelling

The released LNG dispersed in the air resulted in a flammable vapour concentration over the plant not only adjacent to the leak location but also away from it. The autoignition temperature of LNG (primarily methane) is 1004°F (813.15K) [247]. High temperatures and radiation from the fire reach the congested/confined areas, indicating that during the fire, there is a possibility of transitioning the fire into a VCE. The range of radiation and temperature generated during the fire are given in Figures 6-8 and 6-9 respectively.

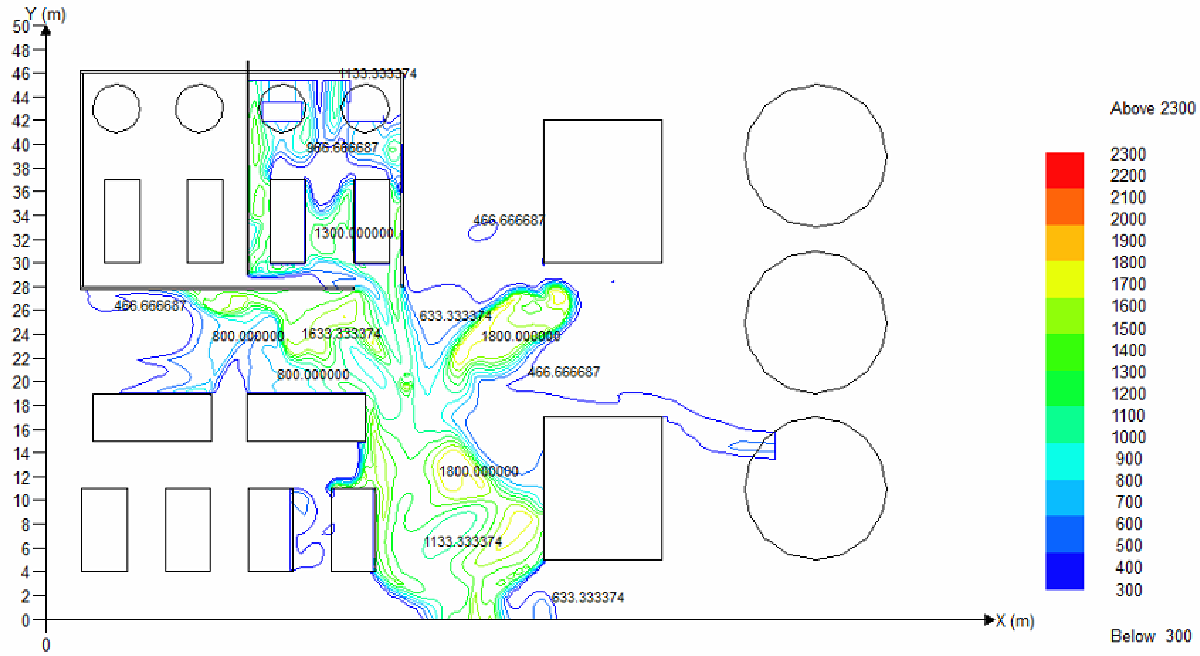

Figure 6-8. Temperature distribution over the layout during the pool fire (K) at 180 s

The maximum temperatures and thermal radiation are 2300K and 80 kW/m^2 respectively. These high temperature and thermal radiation may easily contribute in causing other fires in adjacent areas. The variation of air pressure in the layout in the presence of the dispersed vapour can be a useful information for assessing the potential location of a VCE. During gases dispersion, concentration in the air can create different initial pressure, which is one of the parameters on which the strength of explosion depends [450]. In this study, the maximum pressure developed during the dispersion of LNG vapour is 0.001 barg (illustrated in Figure 6-7). The 1 mbar initial pressure may not have a substantial effect on the strength of a VCE. The output results obtained from the fire modelling and the dispersion modelling show that the transition to a VCE or a flash fire is possible.

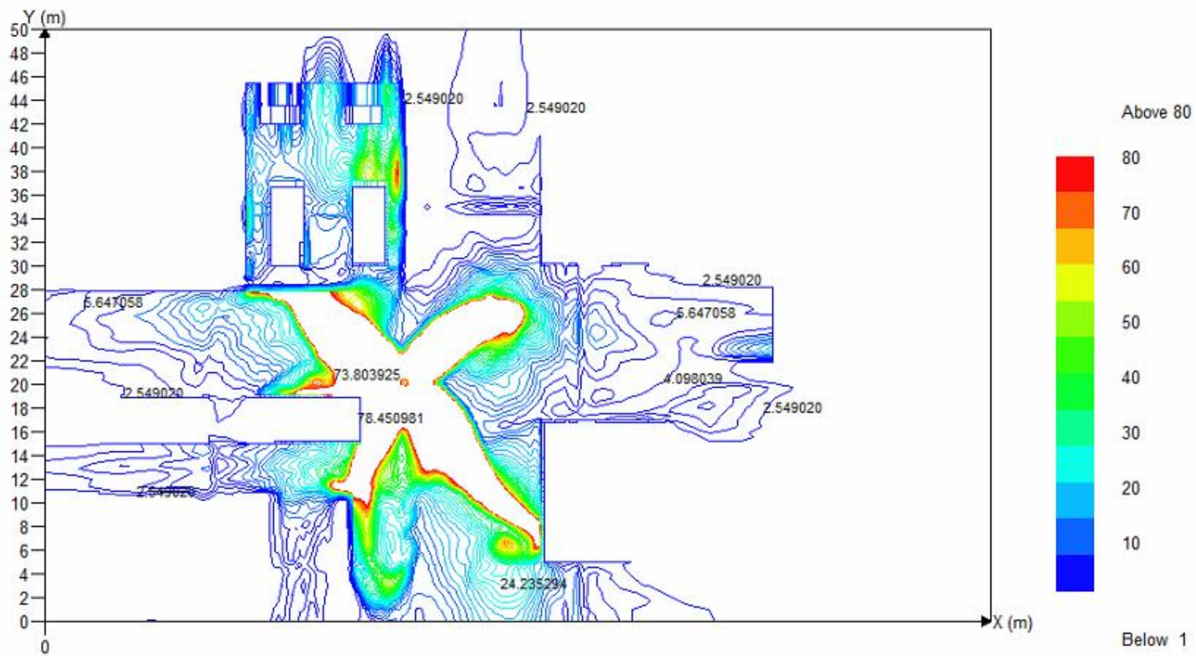

Figure 6-9. Radiation from the fire over the layout (kW/m^2) at 180 s

6.4.2. Thermal radiation impact

The tenability limit for human beings is approximately 2.5 kW/m^2 [451]. The presence of thermal radiation greater than 2.5 kW/m^2 indicates that the fire can have serious effects to human and adjacent assets. The probability of injuries (first and second-degree burn) and the probability of death at different location of the plant are calculated using the thermal radiation. The maximum damage distance for various effects of fire is given in Table 6-7.

Table 6-7. Maximum damage distance for various effects of fire

Effects on humans	**Heat flux (kW/m^2)**	**Maximum damage distance (m)**
100% lethality in 1 min. 1% lethality in 10 s	37.5	26.2
100% lethality in 1 min. Serious injuries in 10 s	25	33.5
1% lethality in 1 min. First degree burns in 10 s	12	36.7
No lethality. 2nd degree burns probable. Pain after exposure of 20 s.	4	39.8
Acceptable limit for prolonged exposure	1.6	43.5

The fire risk index of all grid points was calculated and plotted over the layout as demonstrated in Figure 6-10. The risk index ($Risk_{fe}$) varies from 1 to the maximum value of 10 at the flame surface.

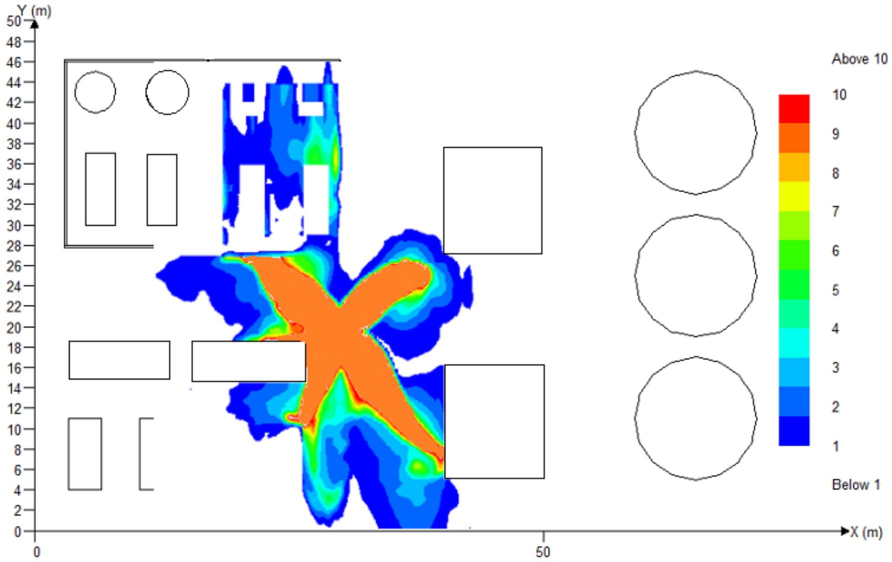

Figure 6-10. Fire risk contour in the layout at 180 s

6.4.3. VCE impact and risk assessment

The impact of the VCE and its subsequent risk are assessed based on the overpressure developed during the VCE. The explosion overpressure ranges from 0 to 2 barg over the layout and high pressures are found in the areas with a high congestion/confinement level as shown in Figure 6-11. The developed pressures are limited within a portion of the congested layout. However, the developed pressures can result in damages to assets and humans in those areas of the facility. The damage distance from the VCE ignition point is illustrated in Table 6-8.

Table 6-8. Damage distance from the VCE ignition point

Effects	**Distance from the ignition point (m)**
100% fatality	4.60
60% fatality	6.25
Fatal distance limit	7.80
Eardrum damage limit	10.30
Safe distance	15

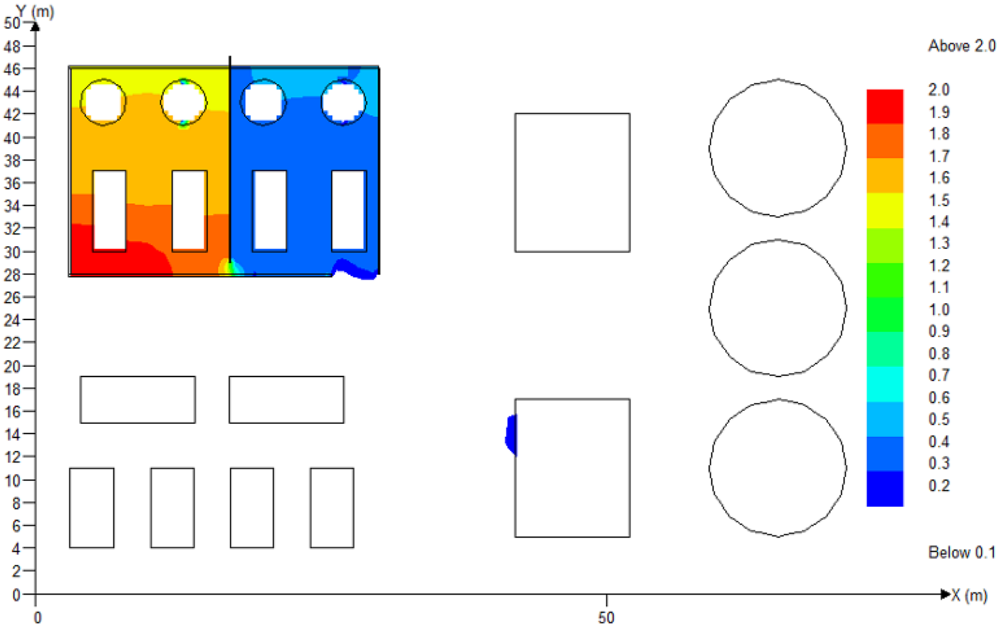

Figure 6-11. VCE pressure over the plant (barg) at 180 s

Using the probit model, the probabilities of injuries or death caused by the overpressure were estimated. Subsequently, the VCE risk index ($Risk_e$) was calculated and plotted over the facility as shown in Figure 6-12. The values of the VCE risk index vary from 1 to 10. Index 1 corresponds to very low risk and the index 10 shows the maximum risk. A high-risk index is found in the congested/confined areas and vice-versa.

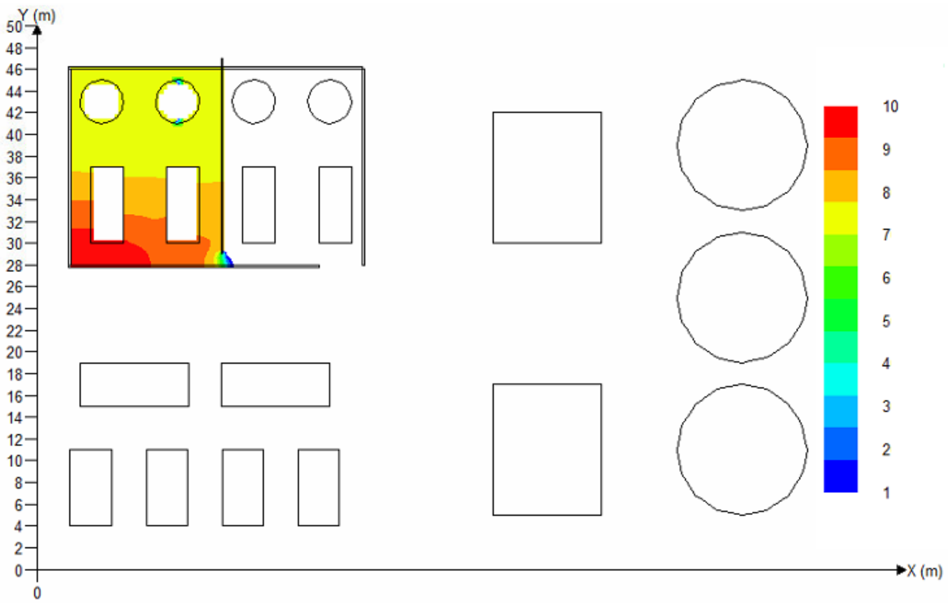

Figure 6-12. Explosion risk profile at 180 s

6.4.4. Combustion product impact

The toxic concentration (mg/m^3) data obtained from the fire and explosion simulations were used for the toxicity assessment. The concentrations of contaminants are high near the fire and explosion locations and confined areas. The toxic concentration of NO_2 is given in Figure 6-13. In confined areas, the concentration of NO_2 is more than 10^5 mg/m^3. Carbon monoxide is very toxic and a concentration of 1.28% leads to death within 2-3 minutes [452]. The toxic concentration of CO is illustrated in Figure 6-14. The higher concentrations of NO_2 are present in larger areas of the layout than those of CO. The obtained NO_2 and CO values are relatively high because these concentrations were measured when there was ongoing fire. Risk values are high around the fire and VCE locations due to higher concentrations of contaminants. This is because a risk value directly depends on exposure duration and concentration.

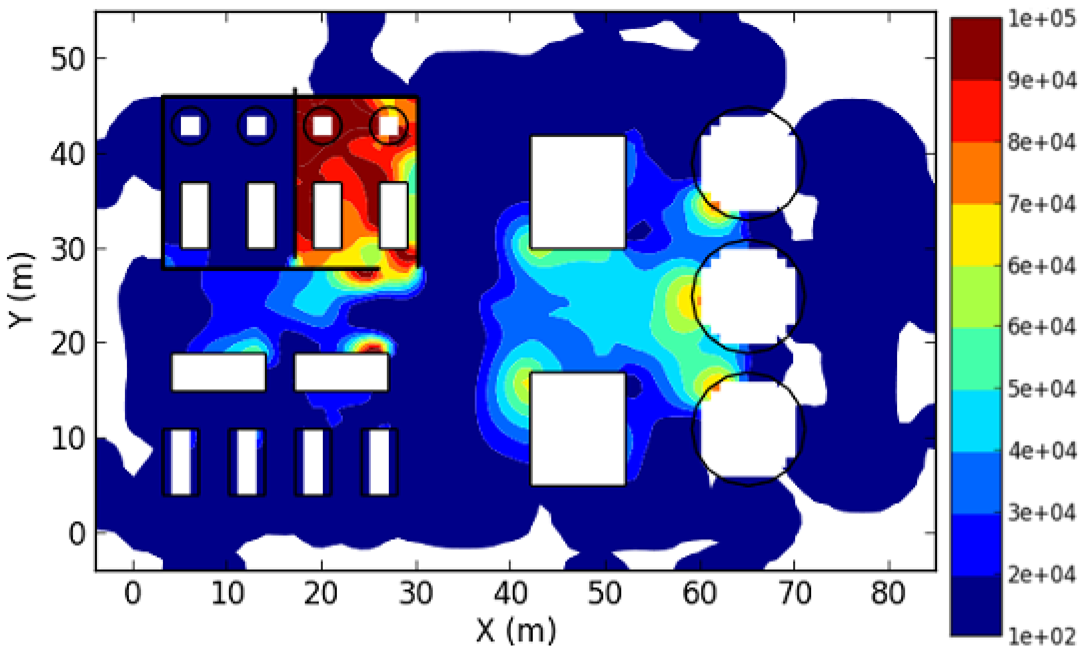

Figure 6-13. Concentration of NO_2 over the layout (mg/m^3) at 180 s

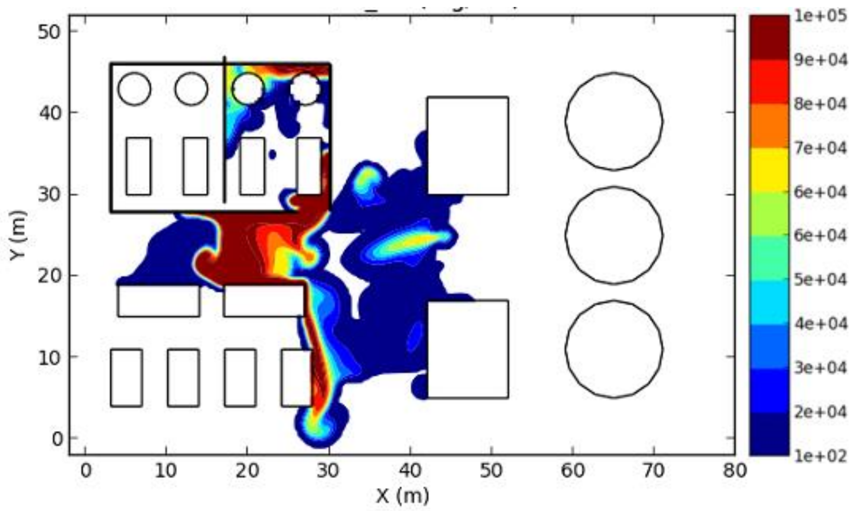

Figure 6-14. Toxic concentration of CO (mg/m^3) at 180 s

6.4.5. Integrated impact during transition of fire to VCE

In most fire and/or explosion events, injury or fatality can be caused by combustion products in addition to radiation or overpressure hazards. Figure 6-15 demonstrates the integrated risk contours in the layout because of thermal radiation and overpressure during the fire and VCE. For simplicity, the range of risk index is normalised between 1 and 10 in the integrated risk profile. High risk indices are available in the fire location and the VCE area due to the inherent nature of those events.

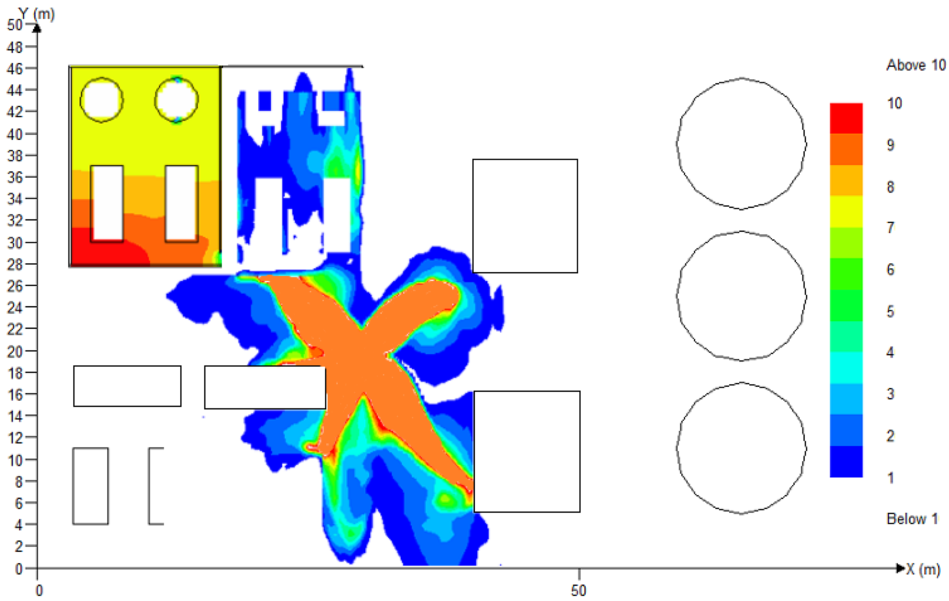

Figure 6-15. Integrated risk profile of the fire and the VCE at 180 s

In toxicity risk assessment, an integrated risk of both contaminants is considered as shown in Figure 6-16. The total combustion product risk shows that significant portions of the facility exceed the acceptable level of risk which is 1. The integrated risk profile of contaminants indicates that the high-risk area is larger than that of the integrated impact of fire and VCE as seen in Figures 6-15 and 6-16. However, due to the short exposure duration, the severity of the combustion products is lower than that of thermal radiation and overpressure. This shows that the impact of transitional events such as fire and VCE along with combustion products is more severe than an individual phenomenon because more portions of the facility exceeded the acceptable level of risk.

The current approach incorporates an additional feature to the previous integrated consequence studies such as Khan and Amyotte [53] and Dadashzadeh *et al.* [54]. Khan and Amyotte [53] incorporated fire, explosion and toxic release damage indices, but did not directly assess the consequence. The adopted technique in Khan and Amyotte [53] cannot be useful for visualizing the area directly affected by fire, explosion and combustion products. The severity of consequence would have been different if the impact of the combustion product was considered by Dadashzadeh *et al.* [54]. During a fire and/or explosion, the potential risk from combustion products can be too simple to ignore because toxicity has been a major cause of death and injury from fires [443].

This paper illustrated only a specific case study. However, any changes in operating conditions such as wind speed, wind direction, snow, rain or other parameters can be incorporated in this approach. Therefore, a range of scenarios can be envisaged and evaluated accordingly.

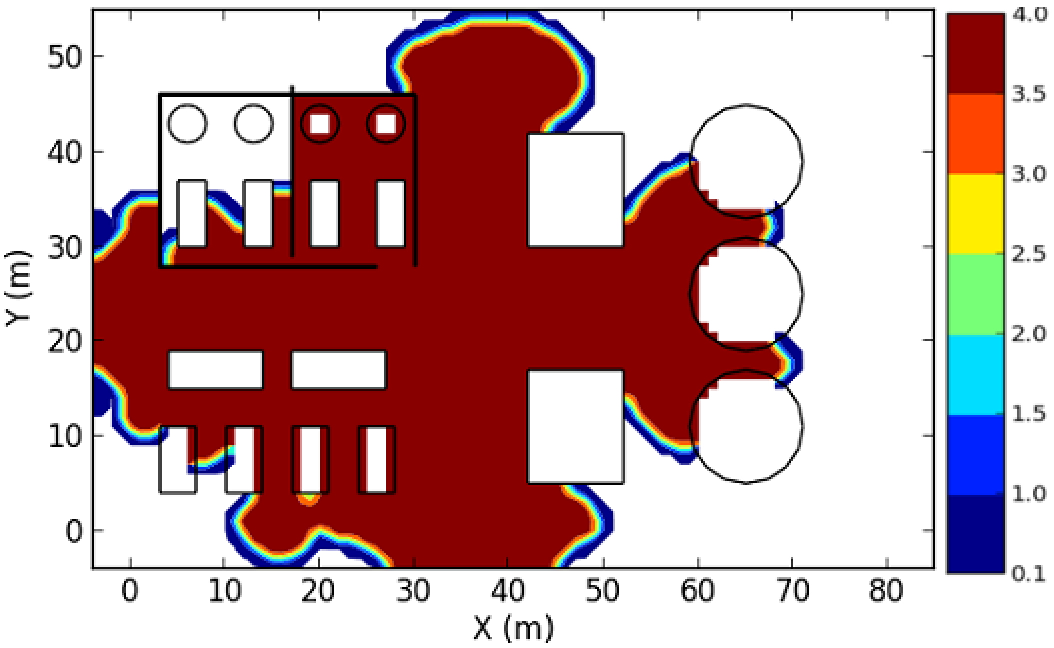

Figure 6-16. Integrated risk of combustion products at 180 s

6.5. Conclusions

In Liquified Natural Gas (LNG) processing facilities, there is a possibility of a fire transitioning into a Vapour Cloud Explosion (VCE) or vice-versa during an accidental release of hydrocarbons as demonstrated in various past fire and explosion accidents. Identification of potential location of transitional events is useful for understanding the occurrence of cascading accident scenarios. A framework has been proposed for modelling transitional events (fire, VCE and combustion product release) and their integrated consequences using Computational Fluid Dynamics (CFD). The proposed framework was applied to a case study considering an accidental LNG release, including vaporisation, a pool fire and a VCE. The impact of each individual event was assessed, and an integrated consequence was modelled using a risk-based approach. The severity of risk during each event in the layout was compared. By analysing the LNG spill, vaporisation, dispersion and subsequent fire in the layout, it is foreseeable that a pool fire can transit to a VCE because of the availability of required suitable conditions such as a flammable vapour concentration, ignition source and congestion/confinement. The risk of the overpressure was limited to confined spaces and was insignificant in other areas. The risk of thermal radiation was present in a larger area in comparison to the VCE. The risk of combustion products was present in a larger area than those of radiation and the overpressure, but its severity was lower due to the short exposure duration. It was found that the integrated risk of transitional events was higher than that of the individual risk.

A change in weather conditions and source terms may affect the outcome of an analysis related to gas leak and dispersion. Responses to gas leak and its dispersion are strongly dependent on these parameters and one set of parameters may not represent all cases. For illustration purpose, this study has presented only a specific case. Once operating conditions such as wind speed, wind direction, snow, rain or other parameter changes, the response need to be evaluated accordingly. The current study serves to highlight the importance of transitional events modelling and expands the scope of the integrated consequence modelling approach. Despite having complex correlations among various parameters involved in LNG spill and subsequent events, the integrated risk profiles can be useful for designing safety systems to mitigate potential effects and risks of thermal radiation, overpressure and combustion products during fire and/or explosion events. Consideration of effects among thermal radiation, overpressure and combustion products in the transitional event modelling, makes the study unique and realistic in the safety analysis of an LNG processing facility.

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Chapter 7

Conclusions and Recommendations

Liquefied Natural Gas (LNG) has gained significant attraction and demands adequate management of the associated safety issues during its production, handling, storage and transportation. Extensive research and recent developments in the LNG value chain have provided better understanding of various hazards posed by LNG release. This chapter summarizes the key findings of this study and recommendations for future work to expand the scope of this study.

This study provides an insight into fire and explosion accident causation, prevention, and impact including the prospect of using alternative fuels for mitigating fire and explosion risks.

7.1. Conclusions

The results of the present study have been extensively assessed and discussed in the previous chapters. The key conclusions are summarised in the following paragraphs.

1. Cryogenic Natural Gas (CrNG), Liquefied Natural Gas (LNG) and methanol have properties more suitable than traditional fuels in mitigating fire risk, and an appropriate management of their hazards could make them a safer option in comparison with the traditional fuels. However, for commercial use at this stage, there exist several uncertainties due to inadequate studies, and technological immaturity.

2. During a minor leakage of LNG on a steel structure, the cryogenic temperature may not cause immediate fracture. However, based on fatigue life analysis of the structure, it is revealed that there is a significant reduction in the design life of the structure due to the ductile to brittle transition characterization.

3. In a typical FLNG processing facility, LNG leaks under pressure from a 750 mm diameter pipe in Mixed Refrigerant (MR) Module of the liquefaction process and the resulting pool fire is found to have greater impact on assets and humans than other accidental release scenarios.

4. An acceptable minor LNG release and dispersion also presents hazardous scenarios for fire and or explosion accidents in a complex layout and this is highly dependent on the

level of equipment congestion in the flow path. The study demonstrated that even after the termination of the leak, the volumetric concentration of LNG vapour was still within the flammable range. This is due to accumulation of pockets of LNG vapour in the spaces between equipment. Moreover, it was found that the retention time of the flammable vapour in the higher congestion level layout was also more than that in the lower congestion level layout under the same operating conditions.

5. Modelling of transitional events such as release, dispersion, fire and explosion highlighted the need for an integrated consequence modelling approach for an accurate risk analysis in any complex layout. This is based on the fact that integrated consequence is more severe than individual consequences.

7.2. Recommendations and future works

The scope of this study can be improved in several ways, specifically in the areas of validation and methodology. The following recommendations are suggested for future work.

1. A change in layout design may affect the outcome of above-mentioned events particularly dispersion and VCE. For illustration purposes, only specific cases are presented in this study. To limit uncertainty of model implementation on different plant design, representative layouts were chosen and required uncertainty analysis was performed in each case. The proposed methodologies are not limited to those given cases only, but can be applied to envisage a range of scenarios with varying operating conditions.

2. In a complex processing facility, the control measures such as ventilation and vapour fence can play a significant role during LNG leakage and vaporisation. Therefore, modelling approaches for a robust design of vapour fence/barrier to avoid propagation of gas to safety critical units, are recommended.

3. LNG (Methane) is considered a simple asphyxiant as it is the main component of LNG. If the LNG vapour does not ignite, the LNG vapour in the air might be high enough to present an asphyxiation hazard to people who may encounter an expanding LNG vaporization plume. Thus, asphyxiation hazard likely to be posed by LNG vapour, needs to be considered for LNG vapour dispersion study in the future.

4. Immediate impact of cryogenic temperature on steel plate has been assessed by considering a pool for a short period of time. However, the long-term impact on micro structure of the exposed material has not been experimentally studied. Therefore, experimental study of this phenomena is recommended.

5. The impact of frostbite or asphyxiation due to cryogenic temperature of LNG during its accidental release has not been included in the integrated consequence modelling. Thus, the integrated modelling approach can be further developed to include the impact of cryogenic temperature on personnel in a complex processing facility.

6. Probability of ignition of LNG vapour during minor leakages is uncertain and needs to be investigated experimentally.

7. Industry heavily depends on leak detection systems that have alarms or trigger interlocking systems during potential toxic and flammable gas release. These systems are put in place to reduce the hazardous effects of release scenarios. An effective design of detection and monitoring systems is therefore vital in managing risks related to LNG vapour dispersion in both onshore and offshore facilities. Moreover, it is equally important to assess the performance of existing detection systems based on leak detector optimisation studies and testing of different detector set points or alarm criteria. The effectiveness of fugitive leak gas monitoring systems and their design in a complex processing facility needs to be assessed based on dispersion characteristics. Therefore, further study in dispersion modelling would need to consider the effectiveness of gas detection and monitoring systems.

8. Proposed models and methods given in chapters 4 and 6 may require a large set of data. The unavailability of such data related to LNG and FLNG makes the uncertainty analysis difficult. When more data becomes available, it is recommended to integrate uncertainty and sensitivity analysis into the currently proposed models. This will help identify critical key parameters and will assist in quantifying the uncertainty associated with the estimated results.

9. The presence of a high degree of congestion/confinement in complex processing facilities may contribute in causing deflagration to detonation transition (DDT). A DDT usually leads to a high pressure and flame speeds and can cause severe impacts than

that of explosion alone. Johnson et al. [453] stated that in some vapour cloud explosions, DDT can occur and the impacts would be more severe as experienced at Buncefield, UK in 2005 [454] and Jaipur, India in 2009 [455]. The possibility of occurrence of DDT on offshore floating platforms has not been considered in this study. The possibility of DDT analysis is recommended for future studies.

10. A change in weather conditions and source terms of leakage may affect the outcome of the afore-mentioned events. Responses to leak, dispersion and fire are strongly dependent to the operating parameters and one set of parameters may not represent all scenarios. A combination of strategies is required with consideration of prevalent operating conditions. For illustration purposes, only specific cases are presented. This study wishes to convey that use of systematic approach help to envisage a range of scenarios and accordingly the responses can be achieved. Once operating conditions such as wind speed, wind direction, snow, rain or other parameter changes, the response need to be evaluated accordingly.

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